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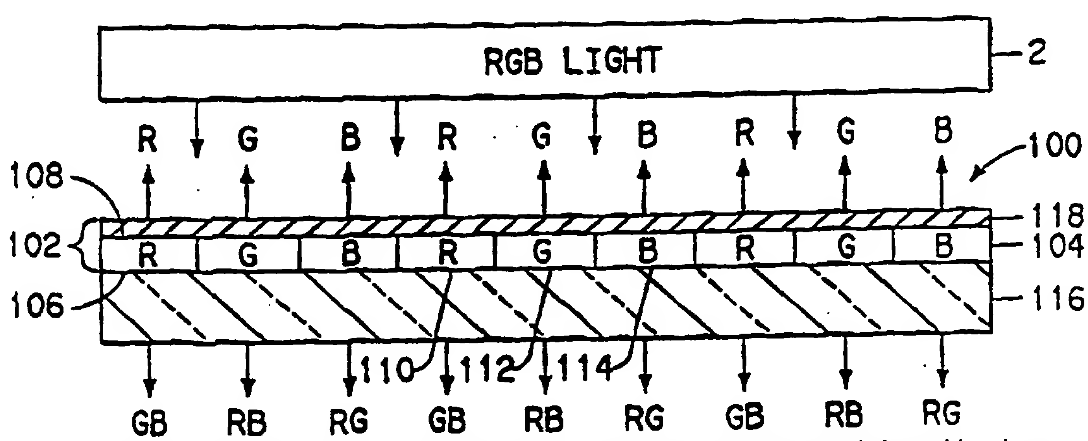
(57) Abstract



The present invention relates to holographic multicolor optical elements for use as multicolor filters in liquid crystal displays and methods of making the elements. The elements can be used as multicolor reflective or transmission filters. The elements can have one, two, three or more holographic recording film layers. Each layer comprises at least first and second pixel volumes containing holographic mirrors and preferably third pixel volumes containing holographic mirrors.

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TITLE OF THE INVENTION

HOLOGRAPHIC MULTICOLOR OPTICAL ELEMENTS FOR USE IN LIQUID CRYSTAL DISPLAYS AND METHODS OF MAKING THE ELEMENTS

CROSS REFERENCES TO RELATED APPLICATIONS

This is related to copending U.S. patent application Serial Number (attorney case number IM-0894) filed June 10, 1994, concurrently with this application.

BACKGROUND OF THE INVENTION

1. Field of the Invention.

This invention relates to holographic multicolor optical elements for use as multicolor filters in liquid crystal displays and methods of making the elements.

2. Description of Related Art.

Multicolor liquid crystal display (LCD) assemblies have many uses including displays in vehicle dashboards, watches, calculators, televisions, computers, video camera view finders, etc. Conventional multicolor LCD assemblies are adapted to display images by transmitting light of different colors, typically red, green or blue, through selected miniature areas of a surface called pixels. Illustrative multicolor LCD assemblies are disclosed in U.S. Patents 4,834,508, 4,878,741, 4,929,060, 4,966,441, 5,089,905, 5,113,274, 5,130,826, 5,150,236 and 5,245,449.

Conventional multicolor LCD assemblies typically use absorptive filters to absorb light except the desired color to be transmitted through each pixel. Illustrative absorptive filters for use in multicolor LCD assemblies are disclosed in U.S. Patents 4,822,718, 4,876,165, 4,966,441, 5,185,059, 5,229,039, and 5,232,634 and in Japanese patent publications JP-04355451, JP-05313009-A and JP-05343631. In certain instances, as in U.S. Patent 4,229,039, the color filter material has a dual role and

also functions as an orientation layer in addition to a color filter.

The absorptive filters rely on a high concentration of particular dyes to insure sufficient absorption of background light and unwanted light of two colors out of the red, green and blue colors. The absorptive dyes typically absorb broad bands of light which restricts the colors, shades and resolution of the display. Further, the absorptive dyes are frequently not highest in transmission at the desired wavelength. Large absorptive filters are difficult to manufacture with high quality especially when pixel size is small throughout the filter. It is also desirable to find a lighter weight alternative to conventional absorptive filters.

SUMMARY OF THE INVENTION

The invention relates to a volume holographic optical element for use as a multicolor filter in a liquid crystal display apparatus, comprising:

a photohardened holographic recording film element comprising at least a first plurality of pixel volumes and a second plurality of pixel volumes arranged in rows and columns;

each one of the first pixel volumes including a volume holographic mirror that passes light with at least one first color (e.g., Red) wavelength band and reflects light with at least another color (e.g., Green) wavelength band; and

each one of the second pixel volumes including a volume holographic mirror that passes light with at least the another color (e.g., Green) wavelength band and reflects light with at least the one color (e.g., Red) wavelength band.

The invention is further directed to a volume holographic optical element for use as a multicolor reflection filter in a liquid crystal display apparatus, comprising:

a photohardened holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that reflects light with a first color (e.g., Red) wavelength band and passes light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that reflects light with the second color (e.g., Green) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that reflects light with the third color (e.g., Blue) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

The invention is further directed to a volume holographic optical element for use as a multicolor transmission filter in a liquid crystal display apparatus, comprising:

a photohardened holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

The volume holographic optical elements are preferably made of holographic recording elements comprising one, two or three holographic recording film elements.

Further, the invention is directed to methods for making the volume holographic optical elements.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention can be more fully understood from the following detailed description thereof in connection with accompanying drawings described as follows.

Figure 1 illustrates a first volume holographic optical element filtering light from a light source in accordance with the present invention.

Figure 2 illustrates the first volume holographic optical element used as a multicolor reflection filter in a liquid crystal display apparatus.

Figure 3 illustrates a first photohardenable holographic recording film element.

Figure 4 shows a photomask that can be used in making the first volume holographic optical element.

Figure 5a illustrates holographically imaging a film element to record a plurality of first holographic mirrors in the film element.

Figure 5b illustrates holographically imaging the film element to record a plurality of second holographic mirrors in the film element.

Figure 5c illustrates holographically imaging the film element to record a plurality of third holographic mirrors in the film element.

Figure 5d illustrates curing the holographic recording film element.

Figure 5e illustrates heating the holographic recording film element.

Figure 6 illustrates a second volume holographic optical element filtering light from a light source in accordance with the present invention.

Figure 7a illustrates the second volume holographic optical element used as a multicolor transmission filter in a liquid crystal display apparatus.

Figure 7b is a graph of relative spectral power versus wavelength for a typical multicolor liquid crystal display light source.

Figure 8 illustrates a second photohardenable holographic recording film element.

Figure 9a illustrates holographically imaging a film element using the first holographic optical element to record a plurality of first, second and third holographic mirrors in the film element.

Figure 9b illustrates curing the holographic recording film element of Figure 9a.

Figure 9c illustrates heating the holographic recording film element of Figure 9b.

Figure 10a illustrates holographically imaging a film element using the second holographic optical element to record a plurality of first, second and third holographic mirrors in the film element.

Figure 10b illustrates curing the holographic recording film element of Figure 10a.

Figure 10c illustrates heating the holographic recording film element of Figure 10b.

Figure 11 illustrates a third volume holographic optical element with a holographic recording film element having a first holographic layer, a second holographic layer and a third holographic layer filtering light from a light source in accordance with the present invention.

Figure 12 illustrates a third photohardenable holographic recording film element.

Figure 13a shows a first filter that can be used in making the third volume holographic optical element.

Figure 13b shows a second filter that can be used in making the third volume holographic optical element.

Figure 14a illustrates imagewise exposing a film element to make selected first layer volumes, second layer volumes and third layer volumes holographically inactive.

Figure 14b illustrates holographically imaging the film element to record a plurality of first, second and third holographic mirrors in the film element.

Figure 14c illustrates heating the holographic recording film element.

Figure 15 illustrates a fourth volume holographic optical element with a holographic recording film element having a first holographic layer and a second holographic layer filtering a light source in accordance with the present invention.

Figure 16 illustrates a fourth photohardenable holographic recording film element.

Figure 17a illustrates holographically imaging the first holographic layer to record third holographic mirrors in the first holographic layer.

Figure 17b illustrates holographically imaging the first holographic layer to record second holographic mirrors in the first holographic layer.

Figure 17c illustrates curing the first holographic layer.

Figure 17d illustrates holographically imaging the second holographic layer to record third holographic mirrors in the first holographic layer.

Figure 17e illustrates holographically imaging the second holographic layer to record first holographic mirrors in the first holographic layer.

Figure 17f illustrates curing the fourth volume holographic optical element.

Figure 17g illustrates heating the fourth volume holographic optical element.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Throughout the following detailed description, similar reference characters refer to similar elements in all figures of the drawings.

I. Holographic Optical Elements and Manufacturing Methods

1.0 First Holographic Optical Element 100

Referring to Figure 1, there is illustrated a first volume holographic optical element 100 in accordance with the present invention. The first volume holographic optical element 100 comprises a first photohardened holographic recording film element 102. In this embodiment, the photohardened holographic recording film element 102 comprises a first single holographic recording film layer 104 having a first surface 106 and a second surface 108. The first holographic recording film layer 104 comprises a first plurality of pixel volumes 110, a second plurality of pixel volumes 112, and a third plurality of pixel volumes 114.

Each one of the first pixel volumes 110 includes a first volume holographic mirror that reflects light with a first color (e.g., Red) wavelength band and passes light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band. Each one of the second pixel volumes 112 includes

a second volume holographic mirror that reflects light with the second color (e.g., Green) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band. Each one of the third pixel volumes 114 includes a third volume holographic mirror that reflects light with the third color (e.g., Blue) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

The holographic mirrors are formed by fringes or gratings. The gratings of all holographic mirrors disclosed herein can be of any shape or slant achieved by conventional holographic methods. The gratings can be conformal gratings which are parallel to the surfaces 106,108 of the recording medium and/or non-conformal gratings which are non-parallel to the surfaces 106,108.

The operation or function of the first volume holographic optical element 100 is illustrated Figure 1. Specifically, a light source 2 is illustrated providing light towards the first photohardened holographic recording film element 100. The light source 2 can emit the first color (e.g., Red) wavelength band, the second color (e.g., Green) wavelength band and/or the third color (e.g., Blue) wavelength band. The light source 2 can emit coherent, substantially coherent or noncoherent light. The letters in Figure 1 designating the color wavelength bands and the associated arrows illustrate whether the element 100 will pass or reflect the specific color wavelength band assuming that the light source 2 emits actinic radiation in such color wavelength band. Preferably, if the light source 2 also emits other color wavelength bands, such wavelength bands would also pass through the first volume holographic optical element 100. The first volume holographic optical element 100 functions the same regardless of which side of the first

volume holographic optical element 100 the light source 2 is positioned.

The first color wavelength band, the second color wavelength band and the third color wavelength band can be any distinct wavelength bands of light. Preferably, the distinct wavelength bands are separated by other wavelength bands. Preferably, light having the first color wavelength band has a bandwidth of at least 5 (and more preferably within about 20-30) nanometers and includes 612 nanometer which appears Red. Preferably, light having the second color wavelength band has a bandwidth of at least 5 (and more preferably within about 20-30) nanometers and includes 545 nanometer which appears Green. Preferably, light having the third color wavelength band has a bandwidth of at least 5 (and more preferably within about 20-30) nanometers and includes 436 nanometer which appears Blue. Unless otherwise indicated, the letters in all pixel volumes throughout the Figures illustrate the color wavelength band(s) that is/are reflected by the pixel volume and all other color wavelengths pass through the pixel volumes. The letter "R" represents a Red wavelength band as an illustration for the first color wavelength band. The letter "G" represents a Green wavelength band as an illustration for the second color wavelength band. The letter "B" represents a Blue wavelength band as an illustration for the third color wavelength band. When two or more of these letters are listed together, it refers to light consisting essentially of the wavelength bands of each of the listed letters.

The first pixel volumes 110, the second pixel volumes 112 and the third pixel volumes 114 can be any shape and in any order in the film layer 104. The volumes 110,112,114 do have sides which are part of the first and second surfaces 106,108 of the film layer 104. Figure 1 depicts one row of a two dimensional array of the volumes 110,112,114. Preferably, the pixels volumes

110,112,114 are ordered in each row of the array in a repeating sequence of one of the first pixel volumes 110, then one of the second pixel volumes 112 and then one of the third pixel volumes 114. The pixel volumes 110,112,114 in adjacent rows can be offset with respect to one another.

The first holographic optical element 100 further optionally comprises a dimensionally stable substrate 116 having a planar surface supporting the first surface 106 of the film layer 104. The first holographic recording film element 102 may further comprise a barrier layer 118 on the second surface 108 of the film layer 104.

Figure 2 illustrates the first volume holographic optical element 100 used as a multicolor reflection filter in a reflective liquid crystal display (LCD) apparatus 120. The reflective liquid crystal display apparatus comprises, in order, a first light polarizer 122, a top or first dimensionally stable support 124, a liquid crystal display element 126, a second light polarizer 128, and the holographic multicolor reflection filter 100. The first light polarizer 122 is for linearly polarizing and passing light, such as ambient light, having a first linear polarization. The top dimensionally stable substrate 124 provides rigidity and overall structural support. The liquid crystal display element 126 is well known by those skilled in the art and is for selectively modifying the polarization of the light passing through an array of cells X,Y,Z such that the polarization of light passing through a first set of the cells X, a second set of the cells Y or a third set of the cells Z can be changed to a second linear polarization. Illustrative liquid crystal display elements are disclosed in the publications cited in the Background of the Invention section of this specification. The second polarization is typically perpendicular to the first polarization. The liquid crystal display element 126 can comprise, in order, a

first circuitry layer 130, a first alignment layer 132, a liquid crystal layer 134, a second alignment layer 136, a second circuitry layer 138, and a leveling layer 140. The circuitry layer 130 provides a first side of an electrical drive circuit capable of modifying a particular first side orientation of liquid crystals in the liquid crystal layer 134 through the first alignment layer 132. The liquid crystal layer 134 confines liquid crystals in cells corresponding to each pixel volume in the reflective filter 100. The second alignment layer 136 introduces a particular second side orientation to the liquid crystals in the liquid crystal layer 134. The second circuitry layer 138 provides a second side of the electrical drive circuit capable of modifying the particular second side orientation of liquid crystals in the liquid crystal layer 134 through the second alignment layer 136. The leveling layer 140 provides a rigid planar surface for the filter 100. The second light polarizer is for passing light from the liquid crystal display element 126 having the second polarization.

In operation, when the liquid crystal display element 126 modifies or rotates the polarization of the light passing through the first set of cells X to the second polarization, the light passes through the second polarizer 128 into the first pixel volumes 110 in which the first volume holographic mirrors reflect light with the first color (e.g., Red) wavelength band back through the liquid crystal display element 126 to a viewer on the same side of the LCD apparatus that ambient light 4 enters the first polarizer 122. When the liquid crystal display element 126 modifies or rotates the polarization of the light passing through the second set of cells Y to the second polarization, the light passes through the second polarizer 128 into the second pixel volumes 112 in which the second volume holographic mirrors reflect light with the second color (e.g., Green) wavelength band back through the liquid crystal display element 126 to the

viewer. When the liquid crystal display element 126 modifies or rotates the polarization of the light passing through the third set of cells Z to the second polarization, the light passes through the second polarizer 128 into the third pixel volumes 114 in which the third volume holographic mirrors reflect light with the third color (e.g., Blue) wavelength band back through the liquid crystal display element 126 to the viewer. In all three cases, other wavelengths of light pass through the filter 100 away from the viewer. Further, light which passes through the liquid crystal display element 126 towards the second polarizer 128, but was not changed by the liquid crystal display element 126 to have the second polarization, is absorbed by the second polarizer 128.

1.1 Method for Making First Element 100

Figure 3 depicts a first holographic recording film element 142 which can be used in making the first photohardened holographic recording film element 100. The first holographic recording film element 142 comprises, in turn, a cover sheet 144, an unimaged, unexposed holographic recording film layer 104', the barrier layer 118 and a dimensionally stable support 146.

A method for making the first volume holographic optical element 100 will now be described starting with the first unimaged, unexposed holographic film element 142. The cover sheet 144 is removed from the first surface 106 of the first holographic film layer 104'. The first surface 106 of the film layer 104' is laminated on the dimensionally stable substrate 116. The support 146 is removed from the barrier layer 118. An anti-reflection plate 148 with a photomask layer 150 is coupled through a first index matching fluid layer 152 to the barrier layer 118. Figure 4 shows a pattern that can be used for the photomask layer 150. The pattern is a two dimensional array of pixels having a first

plurality of pixels B adapted to block light, and a second plurality of pixels P adapted to transmit or pass light. As shown in Figure 4, the array of pixels can have a repeating pattern of the following three rows of pixels:

		Column											
		1	2	3	4	5	6	7	8	9	10	11	...
Row	1	B	B	P	B	B	P	B	B	P	B	B	...
	2	P	B	B	P	B	B	P	B	B	P	B	...
	3	B	P	B	B	P	B	B	P	B	B	P	...

The glass substrate 116 is coupled through a second index matching fluid layer 154 to a reflector 156, such as a front surface mirror. This results in a laminate structure which is depicted in Figure 5a.

Next, a first color (e.g., Red) light source 6 is selected adapted to emit coherent or substantially coherent light consisting essentially of the first color (e.g., Red) wavelength band. Light from the first color (e.g., Red) light source 6 is directed, in turn, through the anti-reflection plate 148, the transparent pixels P of the photomask layer 150, and the first holographic film layer 104' onto the reflector 156. The reflector 156 reflects the light back through the first holographic film layer 104' such that the reflected light interferes with the light passing through the film layer 104' towards the reflector 156. This interference holographically images or imagewise holographically exposes the first holographic film layer 104' to record a plurality of the first volume holographic mirrors, one in each of the first pixel volumes 110.

Next the anti-reflection plate 148 and photomask layer 150 are shifted or moved one pixel in a first direction, i.e., in the X direction illustrated in Figure 4.

Next, as illustrated in Figure 5b, a second color (e.g., Green) light source 8 is selected adapted to emit coherent or substantially coherent light consisting essentially of the second color (e.g., Green) wavelength band. Light from the second color (e.g., Green) light source 8 is directed, in turn, through the anti-reflection plate 148, the transparent pixels P of the photomask layer 150, and the first holographic film layer 104' onto the reflector 156. The reflector 156 reflects the light back through the first holographic film layer 104' such that the reflected light interferes with the light passing through the film layer 104' towards the reflector 156. This interference holographically images or imagewise holographically exposes the first holographic film layer 104' to record a plurality of the second volume holographic mirrors, one in each of the second pixel volumes 112.

Next the anti-reflection plate 148 and the photomask layer 150 are again shifted or moved one pixel in the first or X direction.

Next, as illustrated in Figure 5c, a third color (e.g., Blue) light source 10 is selected adapted to emit coherent or substantially coherent light consisting essentially of the third color (e.g., Blue) wavelength band. Light from the third color (e.g., Blue) light source 10 is directed, in turn, through the anti-reflection plate 148, the transparent pixels P of the photomask layer 150, and the first holographic film layer 104' onto the reflector 156. The reflector 156 reflects the light back through the film layer 104' such that the reflected light interferes with the light passing through the film layer 104' towards the reflector 156. This interference holographically images or imagewise holographically exposes the film layer 104' to record a plurality of the third volume holographic mirrors, one in each of the third pixel volumes 114. This third consecutive holographic imaging step completes the

formation of the unimaged film layer 104' into the imaged film layer 104.

After the anti-reflection plate 148, the photomask layer 150 and the first index matching fluid layer 152 are removed, the resulting laminate structure can be optionally cured, fixed or exposed to substantially polymerize any monomer and fix the holographic mirrors in the laminate structure. This can be accomplished, as illustrated in Figure 5d, by using noncoherent actinic radiation, such as from a broad band ultraviolet light source 12, to flood expose the laminate structure. Throughout this application, the term "broad band ultraviolet light" means light in the spectral region of about 300 through 450 nanometers. This step provides an exposure level of about 100 millijoules per squared centimeter (mJ/cm^2), but the exposure level can be greater. This step typically occurs for about 20 seconds, but can occur longer. This step photohardens or substantially photohardens any remaining photosensitive material in the imaged film layer 104.

After the reflector 156 and the second index matching fluid layer 154 are then removed, the resulting laminate structure can be optionally heated in an oven 14 such as illustrated in Figure 5e. The structure is heated to further harden it and increase its refractive index modulation, its efficiency and the bandwidth of the holographic mirrors. This heating step occurs at a temperature in the range of about 50°C through 200°C, and preferably in the range of about 100°C through 160°C. The greater the temperature the shorter the duration of the heating step. Using the preferred materials, the holographic recording film element can be heated at about 100°C for about 30 minutes.

This results in the first volume holographic optical element 100 illustrated in Figures 1 and 2 where the unimaged, unexposed holographic recording film layer 104' has become the holographic recording film layer 104

holographically imaged with mirrors, optionally fixed (flood exposed) and optionally cured.

2.0 Second Holographic Optical Element 200

Referring to Figure 6, there is illustrated a second volume holographic optical element 200 in accordance with the present invention. The second photohardened holographic recording film element 200 comprises a photohardened holographic recording film element 202 which, in this embodiment, comprises a second single holographic recording film layer 204. The second holographic recording film layer 204 comprises a first plurality of pixel volumes 210, a second plurality of pixel volumes 212, and a third plurality of pixel volumes 214.

Each one of the first pixel volumes 210 includes a first volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and reflects light with at least the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band. Each one of the second pixel volumes 212 includes a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band. Each one of the third pixel volumes 214 includes a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

In all other respects, the second volume holographic optical element 200 can be the same as the first volume holographic optical element 100.

The operation or function of the second volume holographic optical element 200 is illustrated Figure 6. Specifically, the light source 2 is illustrated providing

RGB light towards the second photohardened holographic recording film element 200. Arrows show that the first pixel volumes 210 pass the first color (e.g., R) light and reflect the second and third color (e.g., GB) light back to the RGB light source 2, etc. Again, if the light source 2 also emitted other color wavelength bands, such wavelength bands would preferably pass through the second volume holographic optical element 200. The second volume holographic optical element 200 also functions the same regardless of which side of the second volume holographic optical element 200 the light source 2 is positioned.

Figure 7a illustrates the second volume holographic optical element 200 used as a multicolor transmission filter in a liquid crystal display 220. The transmission liquid crystal display apparatus comprises, in order, a first light polarizer 222, the holographic multicolor transmission filter 200, a liquid crystal display element 226, a first dimensionally stable substrate 224, a second light polarizer 228, and a light assembly 230.

The light assembly 230 can comprise a light source 232, a reflector or intensifier 234, and a prefilter 236. The light source 232 emits light with a first color (e.g., Red) wavelength band, a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band. The light source 232 may also emit light with other wavelength bands. In this case, the prefilter 236 is included to block passage of the other wavelength bands. Figure 7b is a graph of relative spectral power (e.g., milliwatts) versus wavelength (λ) for a typical multicolor liquid crystal display light source. The prefilter 236 could be made to block passage of light having wavelength bands of about 400-425, 474-500, and 575-595 nanometers. Preferably, the prefilter 236 is a volume holographic optical element adapted to pass the first color (e.g., Red) wavelength band, the second color (e.g., Green) wavelength band and the third color (e.g.,

Blue) wavelength band and to reflect other wavelength bands, such as wavelength bands of about 400-425, 474-500, and 575-595 nanometers.

The second light polarizer 228 is for linearly polarizing and passing light from the light assembly 230 having a first polarization. The liquid crystal display element 226 can be the same as the LCD display element 126 and passes light or polarized modified light to the filter 200. The first light polarizer 222 passes light from the filter 200 having the second polarization.

In operation, when the liquid crystal display element 226 modifies or rotates the polarization of the light passing through the first set of cells X to the second polarization, the light passes into the first pixel volumes 210 in which the first volume holographic mirrors pass light with the first color (e.g., Red) wavelength band through the first polarizer 222 to a viewer. When the liquid crystal display element 226 modifies or rotates the polarization of the light passing through the second set of cells Y to the second polarization, the light passes into the second pixel volumes 212 in which the second volume holographic mirrors pass light with the second color (e.g., Green) wavelength band through the first polarizer 222 to the viewer. When the liquid crystal display element 226 modifies or rotates the polarization of the light passing through the third set of cells Z to the second polarization, the light passes into the third pixel volumes 214 in which the third volume holographic mirrors pass light with the third color (e.g., Blue) wavelength band through the first polarizer 222 to the viewer.

2.1 First Method for Making the Second Element 200

Figure 8 illustrates a second photohardenable holographic recording film element 242 which can be used in making the second photohardened holographic recording film element 200. The second photohardenable holographic

recording film element 242 is the same as or similar to the first photohardenable holographic recording film element 142 and comprises a second cover sheet 244, a second photohardenable holographic recording film layer 204' and the second barrier layer 218. However, the support 146 of the first photohardenable holographic recording film element 142 is replaced with a reflective layer 246 coated on a dimensionally stable support 248. The reflective layer 246 can be aluminum or any other reflective material.

A first method for making the second volume holographic optical element 200 will now be described starting with the second holographic recording film element 242 and using the first photohardened holographic optical element 100. First, the cover sheet 244 is removed from a first surface of the unimaged holographic film layer 204'. The first surface of the film layer 204' is laminated on a dimensionally stable substrate 216. The dimensionally stable substrate 116 of the first photohardened holographic optical element 100 is coupled through an index matching fluid layer 252 to the dimensionally stable substrate 216. This results in a laminate structure which is depicted in Figure 9a.

Next, a light source 16 is selected adapted to emit coherent or substantially coherent light comprising the first color (e.g., Red) wavelength band, the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band. Light from the light source 16 is directed, in turn, through the first photohardened holographic recording film element 100, the dimensionally stable substrate 216, and the unimaged second film layer 204' onto the reflective layer 246. The reflective layer 246 reflects the light back through the second film layer 204' such that the reflected light interferes with the light passing through the second film layer 204' towards the reflective layer 246. This interference holographically images the second film layer 204' forming

it into the second imaged holographic recording film layer 204. This is the sole holographic imaging step in this method.

Then the second holographic recording film element 200 can be optionally cured, fixed or exposed to substantially polymerize any monomer and fix the holographic mirrors in the film layer 204. This can be accomplished by removing the first photohardened holographic recording film element 100 and the index matching fluid layer 252. Then, as illustrated in Figure 9b, noncoherent actinic radiation, such as from broad band ultraviolet light source 12, or its equivalent, is used to flood expose the second holographic recording film element 200 as described in relation to Figure 5d.

The reflective layer 246 and the dimensionally stable support 248 are then removed. Figure 9c illustrates another optional step of heating the second holographic recording film element 200 such as in the oven 14 which can be as described in relation to Figure 5e. This results in the second volume holographic optical element 200 illustrated in Figures 6 and 7a where the unimaged, unexposed holographic recording film layer 204' has become the holographic recording film layer 204 holographically imaged with mirrors, optionally fixed (flood exposed) and optionally cured.

2.2 Second Method for Making the Second Element 200

A second method for making the second volume holographic optical element 200 will now be described starting with the first holographic film element 142 and using a master 201 which is another one of the second holographic film elements 200. First, the cover sheet 144 is removed from the first surface 106 of the first unimaged holographic film layer 104'. The first surface 106 of the unimaged film layer 104' is laminated to a dimensionally stable substrate 216'. The dimensionally stable substrate 216' is coupled through a first index

matching fluid layer 254 to an anti-reflection plate 256. The support 146 of the first holographic recording film element 142 is removed. The barrier layer 118 of the unimaged film layer 104' is coupled through a second index matching fluid layer 258 to the dimensionally stable substrate 216 of the master 201. The barrier layer 218 of the master 201 is coupled through an optical adhesive layer 260 to an antihalation layer 262. This results in a laminate structure which is depicted in Figure 10a.

Next, RGB light from light source 16 or an equivalent is directed, in turn, through the anti-reflection layer 256, the unimaged film layer 104', onto the first, second and third mirrors in the first, second and third pixel volumes 210,212,214, respectively, in the film layer 204 of the master 201. The first mirrors pass the first color (e.g., Red) light which passes through the antihalation layer 262 and reflect the second color (e.g., Green) light and the third color (e.g., Blue) light back through the film layer 104' such that the reflected light interferes with the light passing through the film layer 104' towards the first mirrors in the film layer 204 in the master 201. This interference holographically images the film layer 104' forming, copying or reproducing the first mirrors in the holographic recording film layer 104'. The second mirrors pass the second color (e.g., Green) light which passes through the antihalation layer 262 and reflect the first color (e.g., Red) light and the third color (e.g., Blue) light back through the film layer 104' such that the reflected light interferes with the light passing through the film layer 104' towards the second mirrors in the master 201. This interference holographically images the film layer 104' forming, copying or reproducing the second mirrors in the second holographic recording film layer 104'. The third mirrors pass the third color (e.g., Blue) light which passes through the antihalation

layer 262 and reflect the first color (e.g., Red) light and the second color (e.g., Green) light back through the film layer 104' such that the reflected light interferes with the light passing through the film layer 104' towards the third mirrors in the master 201. This interference holographically images the film layer 104' forming, copying or reproducing the third mirrors in the second holographic recording film layer 104'. This single holographic imaging step simultaneously forms, copies or reproduces the unimaged holographic recording film layer 104' into the holographic recording film layer 204 holographically imaged with mirrors. Note that in this case barrier layer 118 is identical or substantially identical to barrier layer 218 and substrate 216' identical or substantially identical to substrate 216.

Then the second holographic recording film element 200 can be optionally cured, fixed or exposed to substantially polymerize any monomer and fix the holographic mirrors in the film element 200. This can be accomplished by removing the anti-reflection plate 256, the first index matching fluid layer 254, the second index matching fluid layer 258, the master 201, the optical adhesive 260 and the antihalation layer 262. Then, as illustrated in Figure 10b, noncoherent actinic radiation, such as from broad band ultraviolet light source 12 or an equivalent, is used to flood expose the second holographic recording film element 200 as described in relation to Figure 5d.

Figure 10c illustrates another optional step of heating the second holographic recording film element 200 in oven 14 which can be as described in relation to Figure 5e. This again results in the second volume holographic optical element 200 illustrated in Figures 6 and 7a.

3.0 Third Holographic Optical Element 300

Referring to Figure 11, there is illustrated a third volume holographic optical element 300 in accordance with the present invention. The third volume holographic optical element 300 effectively functions the same as the second volume holographic optical element 200.

Structurally, like the second volume holographic optical element 200, the third volume holographic optical element 300 comprises a photohardened holographic recording film element 302 comprising a first plurality of pixel volumes 310, a second plurality of pixel volumes 312, and a third plurality of pixel volumes 314. Each one of the first pixel volumes 310 includes a first volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and reflects light with at least the second color (e.g., Green) wavelength band and the third color (e.g., Blue). wavelength band. Each one of the second pixel volumes 312 includes a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band. Each one of the third pixel volumes 314 includes a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

However, in contrast to the second volume holographic recording film element 202, the third volume holographic recording film element 302 comprises a first holographic recording layer 303, a second holographic recording layer 305, and a third holographic recording layer 307. Further, referring to Figure 11, the third volume holographic recording film element 302 preferably comprises, in order, a first barrier layer 309, the first holographic recording layer 303, a second barrier layer

311, the second holographic recording layer 305, a third barrier layer 313, and the third holographic recording layer 307. The third volume holographic optical element 302 may further comprise a dimensionally stable substrate 316 laminated to the third holographic recording layer 307. Other equivalent embodiments exist, such as an embodiment interchanging layers 315 and 319.

Referring back to Figure 11, each one of the first pixel volumes 310, the second pixel volumes 312 and the third pixel volumes 314 comprises a first layer volume 315, a second layer volume 317 and a third layer volume 319. Each of the first volume holographic mirrors comprises a fourth volume holographic mirror and a fifth volume holographic mirror. The fourth mirrors are adapted to pass light with the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band and reflect light with the third color (e.g., Blue) wavelength band. The fourth mirrors are in the third layer volumes 319 of the first pixel volumes 310. The fifth volume holographic mirrors are adapted to pass light with the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band and reflect light with the second color (e.g., Green) wavelength band. The fifth mirrors are in the second layer volumes 317 of the first pixel volumes 310. Each of the second volume holographic mirrors comprises one of the fourth mirrors and a sixth volume holographic mirror. The fourth mirrors are in the third layer volumes 319 of the second pixel volumes 312. The sixth volume holographic mirrors are adapted to pass light with the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band and reflect light with the first color (e.g., Red) wavelength band. The sixth mirrors are in the first layer volumes 315 of the second pixel volumes 312. Each of the third volume holographic mirrors comprise one of the fifth mirrors and one of the sixth mirrors. The fifth mirrors are in the second layer

volumes 317 of the third pixel volumes 314. The sixth mirrors are in the first layer volumes 315 of the third pixel volumes 314. The layer volumes with fourth mirrors are designated with an "R" since they reflect Red and pass other colors. The layer volumes with fifth mirrors are designated with a "G" since they reflect Green and pass other colors. The layer volumes with sixth mirrors are designated with a "B" since they reflect Blue and pass other colors.

The operation or function of the third volume holographic optical element 300 is illustrated Figure 11. Specifically, the light source 12 is illustrated providing RGB light towards the third photohardened holographic recording film element 300. Arrows show that the first pixel volumes 310 pass the first color (e.g., R) light and reflect the second and third color (e.g., GB) light back to the RGB light source 12, etc. Again, if the light source 12 also emitted other color wavelength bands, such wavelength bands would also pass through the third volume holographic optical element 300. The third volume holographic optical element 300 also functions the same regardless of which side of the third volume holographic optical element 300 the light source 12 is positioned.

3.1 First Method for Making the Third Element 300

Figure 12 illustrates a third photohardenable holographic recording film element 342 which can be used in making the third photohardened holographic optical element 300. The third photohardenable holographic recording film element 342 comprises, in order, the first barrier layer 309, a first unimaged holographic recording layer 303', the second barrier layer 311, a second unimaged holographic recording layer 305', the third barrier layer 313, a third unimaged holographic recording layer 307' and the dimensionally stable substrate 316.

Each of the first, second and third holographic recording layers 303',305',307' are fully sensitized.

When the third photohardenable holographic recording film element 342 is substituted for the unimaged holographic recording film layer 204', and the dimensionally stable substrate 216 and the barrier layer 218 laminated on the sides of the film layer 204', in the method described in relation to Figures 9a-c, the third volume holographic optical element 300 is formed as illustrated in Figure 11 (rather than the second volume holographic optical element 200 being formed as illustrated in Figures 6 and 7a). This is a first method for making the third volume holographic optical element 300.

3.2 Second Method for Making the Third Element 300

Furthermore, when the third photohardenable holographic recording film element 342 is substituted for the first photohardenable holographic recording film layer 104', the barrier layer 118 and the substrate 216 in the method described in relation to Figures 10a-c, the third volume holographic optical element 300 is formed as illustrated in Figure 11 (rather than the second volume holographic optical element 200 being formed as illustrated in Figures 6 and 7a). This is a second method for making the third volume holographic optical element 300.

4.0 Fourth Holographic Optical Element 400

A fourth volume holographic optical element 400 is structurally and functionally the same as the third volume holographic optical element 300, except the fourth volume holographic optical element 400 is made of holographic recording layers that are wavelength selective, i.e., not fully sensitized.

4.1 First Method for Making the Fourth Element 400

Figure 13a shows a pattern of a first photomask or filter layer 464 that can be used in a method for making the fourth volume holographic optical element 400. The pattern is a two dimensional array of pixels having a first plurality of pixels 466, a second plurality of pixels 468, and a third plurality of pixels 470. The letter "R" is in each of the first pixels 466 indicating that such pixels 466 only pass Red light. The letter "G" is in each of the second pixels 468 indicating that such pixels 468 only pass Green light. The letter "B" is in each of the third pixels 470 indicating that such pixels 470 only pass Blue light. Figure 13a illustrates a pattern of a second photomask or filter layer 472 which is the same as the first photomask layer 464 with two exceptions. The second photomask layer 472 has rows of pixels that are offset with respect to adjacent rows of pixels. Specifically, the array of pixels can have a repeating pattern of the following two rows of pixels:

Column

		1	A	2	B	3	C	4	D	5	E	6	F	7	G	8	H	9
Row	1	R		G		B		R		G		B		R		G		B
	2		B		R		G		B		R		G		B		R	

Further, in the second filter 472, each pixel is surrounded by a border 474 which should be essentially transparent to the first, second and third wavelength bands of light. This border can be produced by recording no holographic mirrors that reflect the first, second and third wavelength bands in this area. This can be accomplished by requiring the holographic imaging radiation to pass through a photomask which blocks the radiation from recording holograms in the border in forming the filter 472. One suitable filter that can be used would be to use a conventional LCD RGB filter.

Referring to Figures 14a-c, the method for making the fourth volume holographic optical element 400 will now be described starting with the a fourth photohardenable holographic recording film element 442. The fourth photohardenable holographic recording film element 442 is the same as the third photohardenable holographic recording film element 342 illustrated in Figure 12, except in the fourth photohardenable holographic recording film element 442, the first unimaged holographic recording layer 403' is substantially only sensitized to be photosensitive to the first color (e.g., Red) wavelength band, the second unimaged holographic recording layer 405' is substantially only sensitized to be photosensitive to the second color (e.g., Green) wavelength band, and the third unimaged holographic recording layer 407' is substantially only sensitized to be photosensitive to the third color (e.g., Blue) wavelength band.

The first barrier layer 409 of the fourth photohardenable holographic recording film element 440 is laminated to a reflective layer 446 coated on a dimensionally stable support 448. The reflective layer can be a reflective metal, such as aluminum, or any other reflective material. The dimensionally stable substrate 416 of the fourth photohardenable holographic recording film element 442 is coupled to the filter layer 464 by an index matching fluid layer 454.

Then, as illustrated in Figure 14a, actinic radiation is directed from source 18 through the filter layer 464, the fourth photohardenable holographic recording film element 442 onto the reflective layer 446. The reflective layer 446 reflects the light back through the fourth photohardenable holographic recording film element 442. This imagewise exposes the film element 442 to actinic radiation to polymerize monomer in selected first layer volumes 315, second layer volumes 317 and third layer volumes 319 to make the exposed volumes

holographically inactive. More specifically, actinic radiation which passes through a pixel in filter layer 464 labeled "R" passes only the first color (e.g., Red) wavelength band. Only the first film layer 403' is sensitized to the first color (e.g., Red) wavelength band. Thus, the layer volumes 315 in the first film layer 403' under the filter layer pixels labeled "R" become holographically inactive. Actinic radiation which passes through a filter layer pixel labeled "G" passes only the second color (e.g., Green) wavelength band. Only the second film layer 405' is sensitized to the second color (e.g., Green) wavelength band. Thus, the layer volumes 317 in the second film layer 405' under the filter layer pixels labeled "G" become holographically inactive. Actinic radiation which passes through a filter layer pixel labeled "B" passes only the third color (e.g., Blue) wavelength band. Only the third film layer 407' is sensitized to the third color (e.g., Blue) wavelength band. Thus, the layer volumes 319 in the third film layer 407' under the filter layer pixels labeled "B" become holographically inactive.

Then the filter layer 464 and the index matching fluid layer 454 are removed. Next, as illustrated in Figure 14b, coherent or substantially coherent light, such as from light source 16 or its equivalent, is directed, in turn, through the film element 442 onto the reflective layer 446. The reflective layer 446 reflects the light back through the film element 442 such that the reflected light interferes with the light directly from the source 16. This interference holographically images the film element 442 recording the multi-layer volume holographic optical element 400. More specifically, holographic mirrors form in non-inactive layer volumes 315 of the first layer 403' where the mirrors will reflect light having the first color (e.g., Red) wavelength band and pass all other wavelength bands. Holographic mirrors form in non-inactive layer volumes

317 of the second layer 405' where the mirrors will reflect light having the second color (e.g., Green) wavelength band and pass all other wavelength bands. Holographic mirrors form in non-inactive layer volumes 319 of the third layer 407' where the mirrors will reflect light having the third color (e.g., Blue) wavelength band and pass all other wavelength bands. This simultaneously holographically images the first layer 403', the second layer 405' and the third layer 407' into imaged layers 403, 405 and 407, respectively.

Then the reflective layer 446 and the dimensionally stable support 448 are removed. The fourth holographic recording film element 400 does not need to be cured. Figure 14c illustrates another optional step of heating the fourth holographic recording film element 400 which can be as described in relation to Figure 5e. This results in the fourth volume holographic optical element 400.

5.0 Fifth Holographic Optical Element 500

Referring to Figure 15, there is illustrated a fifth volume holographic optical element 500 in accordance with the present invention. The fifth volume holographic optical element 500 effectively functions the same as the second volume holographic optical element 200.

Structurally, like the second volume holographic optical element 200, the fifth volume holographic optical element 500 comprises a photohardened holographic recording film element 502 comprising a first plurality of pixel volumes 510, a second plurality of pixel volumes 512, and a third plurality of pixel volumes 514. Each one of the first pixel volumes 510 includes a first volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and reflects light with at least the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band. Each one of the second pixel volumes

512 includes a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band. Each one of the third pixel volumes 514 includes a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

In contrast to the second volume holographic recording film element 202, the fifth volume holographic recording element 502 only has a first holographic recording layer 503 and a second holographic recording layer 505. Further, the fifth volume holographic recording film element 502 preferably comprises, in order, a first barrier layer 509, the first holographic recording layer 503, a second barrier layer 511, and the second holographic recording layer 505. The fifth volume holographic optical element 502 may further comprise a dimensionally stable substrate 516 laminated to the second holographic recording layer 505.

Each one of the first pixel volumes 510, the second pixel volumes 512 and the third pixel volumes 514 comprises a first layer volume 515 and a second layer volume 517. Each of the first volume holographic mirrors comprises a fourth volume holographic mirror and a fifth volume holographic mirror. The fourth mirrors are adapted to pass light with the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band and reflect light with the third color (e.g., Blue) wavelength band. The fourth mirrors are in the first layer volumes 515 of the first pixel volumes 510. The fifth volume holographic mirrors are adapted to pass light with the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band and reflect light with the second color (e.g., Green)

wavelength band. The fifth mirrors are in the second layer volumes 517 of the first pixel volumes 510. Each of the second volume holographic mirrors comprises one of the fourth mirrors and a sixth volume holographic mirror. The fourth mirrors are in the second layer volumes 517 of the second pixel volumes 512. The sixth volume holographic mirrors are adapted to pass light with the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band and reflect light with the first color (e.g., Red) wavelength band. The sixth mirrors are in the first layer volumes 515 of the second pixel volumes 512. Each of the third volume holographic mirrors comprise one of the fifth mirrors and one of the sixth mirrors. The fifth mirrors are in the second layer volumes 517 of the third pixel volumes 514. The sixth mirrors are in the first layer volumes 515 of the third pixel volumes 514. The layer volumes with fourth mirrors are designated with an "R" since they reflect Red and pass other colors. The layer volumes with fifth mirrors are designated with a "G" since they reflect Green and pass other colors. The layer volumes with sixth mirrors are designated with a "B" since they reflect Blue and pass other colors.

The operation or function of the fifth volume holographic optical element 500 is illustrated Figure 15. Specifically, the light source 2 is illustrated providing RGB light towards the fifth photohardened holographic recording film element 500. Arrows show that the first pixel volumes 510 pass the first color (e.g., R) light and reflect the second and third color (e.g., GB) light back to the RGB light source 2, etc. Again, if the light source 2 also emitted other color wavelength bands, such wavelength bands would also pass through the third volume holographic optical element 500. The fifth volume holographic optical element 500 also functions the same regardless of which side of the third volume holographic optical element 500 the light source 2 is positioned.

5.1 First Method for Making the Fifth Element 500

Figure 16 illustrates a fifth photohardenable holographic recording film element 542 which can be used in making the fifth photohardened holographic optical element 500. The fifth photohardenable holographic recording film element 542 comprises, in order, the first barrier layer 509, a first unimaged holographic recording layer 503', a second barrier layer 511, a second unimaged holographic recording layer 505' and a dimensionally stable substrate 516. The first holographic recording layer 503' is at least sensitized to the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band. The first holographic recording layer 503' is either not sensitized to the second color (e.g., Green) wavelength band or sensitized much less to the second color (e.g., Green) wavelength band than it is sensitized to the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band. The second holographic recording layer 505' is at least sensitized to the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band. The second holographic recording layer 505' is either not sensitized to the first color (e.g., Red) wavelength band or sensitized much less to the first color (e.g., Red) wavelength band than it is sensitized to the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band.

When the fifth photohardenable holographic recording film element 542 is substituted for the unimaged holographic recording film layer 204', and the dimensionally stable substrate 216 and the barrier layer 218 laminated on the sides of the film layer 204', in the method described in relation to Figures 9a-c, the fifth volume holographic optical element is formed as illustrated in Figure 15 (rather than the second volume holographic optical element being formed as illustrated

in Figures 6 and 7a). This is a first method for making the fifth volume holographic optical element 500.

5.2 Second Method for Making the Fifth Element 500

Furthermore, when the fifth photohardenable holographic recording film element 542 is substituted for the first photohardenable holographic recording film layer 104', the substrate 216 and the barrier layer 118 in the method described in relation to Figures 10a-c, the fifth volume holographic optical element is formed as illustrated in Figure 15 (rather than the second volume holographic optical element 200 being formed as illustrated in Figures 6 and 7a). This is a second method for making the fifth volume holographic optical element.

6.0 Sixth Holographic Optical Element 600

A sixth volume holographic optical element 600 is structurally and functionally the same as the fifth volume holographic optical element 500, except the sixth volume holographic optical element 600 is made of holographic recording layers that are fully sensitized.

6.1 Method for Making the Sixth Element 600

A method for making the sixth volume holographic optical element 600 will now be described starting with a photohardenable holographic recording film element which is identical to the second photohardenable holographic recording film element 242, except its layers will be identified by 600 numbers, rather than 200 numbers, and its film layer will be designed by the number 605'. First, the cover sheet 644 is removed from the first surface of the unimaged holographic film layer 605'. The first surface of the film layer 605' is laminated on a dimensionally stable substrate 616. The dimensionally stable substrate 616 is coupled through an index matching fluid layer 692 to the dimensionally stable substrate 682

which is coated with a first photomask layer 672. This results in a laminate structure which is depicted in Figure 17a.

Next, the third color coherent or substantially coherent light from light source 10 or its equivalent is directed, in turn, through the first photomask layer 672, and the second photohardened holographic recording film layer 605' onto the reflective layer 646. The reflective layer 646 reflects the light back through the film layer 605' such that the reflected light interferes with the light passing through the film layer 605' towards the reflective layer 246. This interference holographically images or imagewise holographically exposes the film layer 605' with the Blue light which records the fourth volume holographic mirrors in the second layer volumes 617 of the second pixel volumes 610.

Referring to Figure 17b, a second photomask layer 674 coated on a dimensionally stable substrate 684 is substituted for the first photomask layer 672 coated on the dimensionally stable substrate 682. The substrate 684 is coupled to the substrate 616 through an index matching fluid layer 694. Then, the second color coherent or substantially coherent light, such as from the light source 8, is directed, in turn, through the second photomask layer 674, the film layer 605' onto the reflective layer 246. The reflective metal layer 246 reflects the light back through the film layer 605' such that the reflected light interferes with the light passing through the film layer 605' towards the reflective layer 246. This interference holographically images or imagewise holographically exposes the film layer 605' with the Green light to record the fifth volume holographic mirrors in the second layer volumes 617 of the first pixel volumes 610 and the third pixel volumes 614. This completes the conversion of the unimaged film layer 605' to the imaged film layer 605.

Then the second photomask layer 674, its dimensionally stable substrate 684 and the index matching fluid layer 694 can be removed. The resulting laminate can be optionally cured or fixed to substantially polymerize any monomer and fix the holographic mirrors in the laminate. As illustrated in Figure 17c, noncoherent actinic radiation, such as from source 12, is used to flood expose the laminate as described in relation to Figure 5d.

Referring to Figure 17d, a third photomask layer 676 coated on a dimensionally stable substrate 686 is coupled to the dimensionally stable substrate 616 with an index matching fluid 696. Further, an unimaged fully sensitized holographic recording film layer 603' and a first barrier layer 609 are located between the second barrier layer 611 and the reflective metal layer 246. Then, the third color coherent or substantially coherent light, such as from the light source 10, is directed, in turn, through the third photomask layer 676, the film layer 605, and the unimaged film layer 603' onto the reflective layer 246. The reflective layer 246 reflects the light back through the film layer 603' such that the reflected light interferes with the light passing through the film layer 603' towards the reflective layer 246. This interference holographically images or imagewise holographically exposes the film layer 603' with the third color (e.g., Blue) light to record the fourth volume holographic mirrors in the first layer volumes 615 of the first pixel volumes 610.

Referring to Figure 17d, a fourth photomask layer 678 coated on a dimensionally stable substrate 688 is coupled to the dimensionally stable substrate 616 with the index matching fluid 698. Then, the first color light, such as from the light source 6, is directed, in turn, through the fourth photomask layer 678, the film layer 605, and the first film layer 603' onto the reflective layer 246. The reflective layer 246 reflects

the light back through the first film layer 603' such that the reflected light interferes with the light passing through the first film layer 603' towards the reflective layer 246. This interference holographically images or imagewise holographically exposes the first film layer 603' with the first color (e.g., Red) light to record the sixth volume holographic mirrors in the first layer volumes 615 of the second pixel volumes 612 and the third pixel volumes 614. This completes the conversion of the unimaged film layer 603' to the imaged film layer 603.

Then the fourth photomask layer 678, its dimensionally stable substrate 688 and the index matching fluid layer 698 can be removed. The resulting laminate can be optionally cured or fixed to substantially polymerize any monomer and fix the holographic mirrors in the laminate. As illustrated in Figure 17f, noncoherent actinic radiation, such as from the light source 12, is used to flood expose the laminate as described in relation to Figure 5d.

Figure 17g illustrates another optional step of heating the laminate which can be as described in relation to Figure 5e. This results in the sixth volume holographic optical element 600.

II. Materials and/or Commercial Availability

The dimensionally stable substrates 116, 124, 216, 224, 316, 416, 516, 616, 682, 684, 686, and 688 can be made of rigid transparent materials and preferably are made of glass or plastic. Each of these substrates can be the same or different.

The barrier layers 118, 218, 309, 311, 313, 409, 411, 413, 509, 511, 609, and 611 are optional and are useful to prevent interlayer diffusion of dye sensitizer. When used, they are required to be transparent if irradiation is to be carried out through them. Each of these barrier layers can be the same or different. Such

barrier layers can be made of transparent polymers and are preferably made of polyvinyl alcohol (PVA).

The cover sheets 144, 244 function to protect the film layers until ready for use. These cover sheets generally are a polymer film, such as polyethylene, polypropylene, or polyethylene terephthalate.

The unimaged, unexposed holographic film layers 104', 204', 303', 305', 307', 403', 405', 407', 503', 505', 603', and 605' are made of a photohardenable or photosensitive material. Each of these layers can be the same or different, unless otherwise specified. Holograms are recorded in materials that produce a spatial pattern of varying refractive index, rather than optical density, when exposed to light. Holographic recording materials are described in a number of references, such as, L. Solymer and D. J. Cook, Volume Holography and Volume Gratings, Academic Press, New York, 1981, Chapter 10, pages 254-304; and W. K. Smothers, B. M. Monroe, A. M. Weber and D. E. Keys, Photopolymers for Holography, SPIE Vol. 1212, Practical Holography IV (1990). Early developments in holography are described by E. N. Leith and J. Upatnieks, Scientific American, 212(6), 24-35 (June 1965). A useful discussion of holography is presented By C. C. Guest entitled Holography in Encyclopedia of Physical Science and Technology, Vol. 6, pages 507-519, R. A. Myers, Ed., Academic Press, Orlando, Fl, 1987. Preferred recording materials for use in this invention are photopolymerizable compositions, dichromated gelatin, and silver halide emulsions.

Photopolymerizable compositions are disclosed in Haugh, U.S. Patent 3,658,526; Chandross, U.S. Patent 3,993,485; and Fielding, U.S. Patents 4,535,041 and 4,588,664. Preferred photopolymerizable compositions are disclosed in Keys, U.S. Patent 4,942,102; Monroe, U.S. Patent 4,942,112; Smothers, U.S. Patent 4,959,284; Trout, U.S. Patent 4,963,471; Smothers, U.S. Patent 5,236,808; and Smothers, U.S. Patent 5,256,520; as well as in U.S.

Patent application serial numbers 08/146,817 and 08/146,816. The compositions used in the preferred recording film element are dry films.

As used throughout this specification, "fully sensitized" means that the material is photosensitive to light from about 400 to about 700 nanometers wavelengths which includes the entire visible range of light. See U.S. Patent 4,917,977 which discloses methods for making fully sensitized, and non-fully sensitized or wavelength selectively sensitized, holographic materials. In addition, see the following related and more recent patents disclosing use of photosensitizers: Smothers, U.S. Patent 5,204,467; Smothers, U.S. Patent 5,236,808; and Smothers, U.S. Patent 5,256,520.

The dimensionally stable supports 146, 248, 448 are required to be transparent if irradiation is to be carried out through the supports. Preferred materials for the support 146 are polymer films, such as polyethylene, polypropylene, cellulose, and polyethylene terephthalate.

Antireflection plates 148, 156 function to prevent back reflection of imaging light and are commercially available from CVI Laser Corporation with offices at Albuquerque, New Mexico.

The photomask layers 150, 672, 674, 676, 678 function to block all light from passing through the layers and can be made of patterned chromium or silver halide on glass. Alternatively, imagewise radiation can be carried out through a half-tone or continuous tone transparency. Other means of imagewise irradiation include exposure through a transmissive device, such as an absorptive filter, and exposure using a scanning laser, electron beam, or the like.

The index matching fluid layers 152, 154, 252, 254, 258, 454, 692, 694, 696, 698 are preferably hydrocarbons and most preferably are Isopar® L available from Chemcentral Corporation with offices at Southwestern

Pennsylvania 19399 and Cargille A1.59 available from R.P. Cargille Laboratories, Inc. at Cedar Grove, New Jersey 07009.

Optical adhesive layers 260 function to adhere adjacent layers with proper index matching between layers. Preferred optical adhesive materials are transparent and include polyurethane, and proprietary products commercially available from Norland Products, Inc. with offices at New Brunswick, New Jersey 08902

The antihalation layer 262 functions to absorb light and prevent back reflection. Suitable antihalation layers are black spray paint on float glass or highly absorbing films such as Chronar® commercially available from E. I. du Pont de Nemours and Company of Wilmington, Delaware.

III. Examples

The advantageous properties of this invention can be observed by reference to the following examples which illustrate, but do not limit, the invention. In these Examples, parts and percents are by weight unless otherwise indicated. Terms or abbreviations used throughout the examples are defined the following glossary.

GLOSSARY

DE (%)	Diffraction efficiency expressed as a percent; DE (%) = $I_{dif}/I_o \times 100$, where I_{dif} is the intensity of the diffracted beam of actinic radiation and I_o is the intensity of the incident beam corrected for absorption in the film sample and for spurious reflections off the film sample
FC-430	Fluorad® FC-430; fluoroaliphatic polymeric esters; CAS 11114-17-3; 3M Company, St. Paul, MN
GA2-red	OmniDex® GA2-red color tuning film (CTF); E. I.

du Pont de Nemours, Inc., Wilmington, DE; OmniDex® is a registered trademark of E. I. Du Pont de Nemours and Company

Isopar® L	An aliphatic hydrocarbon product; Exxon Company, Houston, TX
JAW	Cyclopentanone, 2,5-bis[2,3,6,7-tetrahydro-1H,5H-benzo[i,j]quinolizin-9-yl)methylene]-
MMT	4-Methyl-4H-1,2,4-triazole-3-thiol; CAS 24854-43-1
Mylar® film	Polyethylene terephthalate film; registered trademark of E. I. du Pont de Nemours and Company, Wilmington, DE
NVC	N-Vinyl carbazole; 9-vinyl carbazole; CAS 1484-13-5
Photomer® 4039	Phenol ethoxylate monoacrylate; CAS 56641-05-5; Henkel Process Chemical Company, Ambler, PA
PI-B	4,5-diphenyl-1-[4,5-diphenyl-2-(2,3,5-trichlorophenyl)-2H-imidazol- 2-yl]-2-(2,3,5-trichlorophenyl)-1H-imidazole
PVA	Poly(vinyl alcohol)
Sartomer 349	Ethoxylated bisphenol A diacrylate; CAS 24447-78-7; Sartomer Company, West Chester, PA
SD-A	3-[(1-ethyl-1,2,3,4-tetrahydro-6 quinolinyl)methylene]-2,3-dihydro-4H-1-benzopyran-4-one; CAS 75535-23-8

SD-B 2,4-bis[(3-ethyl-2(3H)-benzothiazolylidene) ethylidene]-8-methyl-8-azabicyclo[3.2.1]octan-3-one; CAS 154482-35-6

SD-C 1-ethyl-2-[[3-[(1-ethyl-1,3-dihydro-5-methoxy-3,3-dimethyl-2H-indol- 2-ylidene)methyl]-2-hydroxy-4-oxo-2-cyclobuten-1-ylidene]methyl]-5-methoxy-3,3-dimethyl-3H-indolium hydroxide inner salt; CAS - none on computer files (STN International)

Spot# Area/pixel/region (identified by number) of the HRF that is imaged in the examples of this specification

TFE Tetrafluoroethylene

TMPTMA Trimethylol propane trimethacrylate

VAc Vinyl acetate

VOH Vinyl alcohol

(λ)max (nm) Wavelength of actinic radiation showing the maximum diffraction efficiency (DE (%)) from the transmission spectrum of a holographic mirror

EXAMPLE 1

This example demonstrates the ability to record high efficiency single-color mirrors at separate regions in a single holographic photopolymer layer, which is required for high efficiency volume holographic optical elements and multicolor holographic filters.

To prepare the holographic (photopolymer) recording film which is utilized in this example, a coating solution was prepared containing 66.0 weight % of tetrafluoroethylene/vinyl acetate (TFE/VAc) binder copolymer (containing 19.4 mole % TFE and 80.6 mole %

vinyl acetate and having inherent viscosity = 1.48 deciliters/gram measured at 30°C), 21.0 weight % of Photomer® 4039, 6.0 weight % of NVC, 3.0 weight % of Sartomer 349, 3.0 weight % of PI-B, 1.0 weight % of MMT, 0.22 weight % of FC-430, 0.075 weight % of JAW, and 0.034 weight % of SD-C in 19:1 dichloromethane/methanol.

The solution was extrusion dye coated onto a 50 µm Mylar® base sheet at a speed of about 31 ft/min (15 cm/sec) using a web coater. The solvent was evaporated by passing the coated film through a three zone drier. The first zone was at 120°F (49°C), the second at 140°F (60°C), and the third at 160°F (71°C). A coversheet of 23 micron Mylar® (polyethylene terephthalate film) was laminated to the coating as it exited the drier. Dry coating thickness of the holographic photopolymer was 20 µm between a 23µm Mylar® cover sheet and 50µm Mylar® base sheet. The coversheet was removed from the photopolymer and the tacky photopolymer was laminated to a section of 100mmx125mmx3.2mm float glass. Excess film was trimmed away so that the laminated film fit within the edges of the glass substrate. The base sheet was left in place during subsequent processing. We refer to the structure of base/holographic photopolymer and glass plate as the imaging plate. The film side of the imaging plate was coupled to an anti-reflection (AR) plate using Isopar® L (Exxon) to provide a good match of the refractive index of the film to the AR plate. On the opposite side of the imaging plate, a front-surface aluminum mirror was coupled to the surface using the same index matching fluid. Pressure was applied to the stack of plates to provide thin, even index matching fluid layers. The stack of plates was then mounted in a conventional plate holder mounted on an imaging stage and allowed to settle for more than 30 seconds.

An argon ion laser with emissions at 458nm, a diode-pumped, frequency-doubled YAG laser with emissions at 532nm and a krypton ion laser with emissions at 647nm

were combined by appropriate dichroic mirrors in the conventional way to form a 3-color laser beam. This 3-color beam was passed through achromatic optics to form an expanded, collimated, 3-color beam. A shutter was installed to allow each color to be introduced separately (for the imaging of individual regions (spots or pixels) with one color wavelength of the three available in the 3-color beam). The imaging plate was rotated on the imaging stage such that the 3-color laser beam direction was perpendicular to the imaging stack.

Four holographic mirrors at each of three imaging wavelengths were formed, each one being located in a separate region (spot or pixel), by exposing with a collimated single-color laser beam oriented perpendicular to the film plane and passing, in order, through the anti-reflection plate, Isopar® L layer, base sheet, holographic photopolymer, glass plate and Isopar® L layer and then reflecting back onto itself off the mirror. The exposure energy of holographic mirrors imaged at 647nm was 100 mJ/cm^2. The exposure energy of holographic mirrors imaged at 532nm was 20 mJ/cm^2. The exposure energy of holographic mirrors imaged at 458nm was 10 mJ/cm^2. Each set of four 20 mm diameter regions was formed on the plate using identical imaging conditions. The imaging plate was translated to an unimaged region of the film plate after each exposure and allowed to settle for 30 seconds before a subsequent exposure. After imaging, the AR plates, front surface mirror and Isopar® L layers were removed.

The imaging plate was overall exposed to ultraviolet and visible light from a Theimer-Strahler #5027 mercury-arc lamp (Exposure Systems Corp., Bridgeport, Conn.) mounted in a Douthitt DCOP-X exposure unit (Douthitt Corp., Detroit, Michigan) for 120 sec (about 150 mJ/cm^2). The imaging plate was thermally processed by heating at 120°C for 2 hours in a forced-air convection oven.

The transmission spectrum of the holographic mirrors was recorded using a standard double-beam spectrophotometer (Perkin-Elmer model Lambda-9) with the sample beam oriented perpendicular to the hologram film plane. The results are shown in Table 1 and demonstrate that high efficiency holographic mirrors each having a single wavelength have been formed at the three different wavelengths (448, 522, and 635 nm) at different spots (regions or pixels) within a single holographic photopolymer layer.

TABLE 1

	red	exposure	green	exposure	blue	exposure
spot #	λmax (nm)	DE (%)	λmax (nm)	DE (%)	λmax (nm)	DE (%)
1	635.0	99.6				
2	635.2	99.5				
3	635.2	99.5				
4	635.8	99.4				
5			522.4	99.9		
6			522.2	99.9		
7			522.0	99.9		
8			522.6	99.9		
9					448.0	99.9
10					448.4	99.9
11					448.4	99.9
12					448.2	99.9

EXAMPLE 2

This example demonstrates the imaging of a three-color holographic optical element and a three-color imaging through the holographic optical element designed to block one of the three imaging wavelengths, allowing the other two to pass through and record into the copy film.

To prepare the holographic (photopolymer) recording film which is utilized in this example, a coating solution was prepared containing 66.0 weight % of tetrafluoroethylene/vinyl acetate (TFE/VAc) binder copolymer (containing 20.0 mole % TFE and 80.0 mole % vinyl acetate and having inherent viscosity = 1.45 deciliters/gram measured at 30°C), 21.0 weight % of Photomer® 4039, 6.0 weight % of NVC, 3.0 weight % of Sartomer 349, 3.0 weight % of PI-B, 1.0 weight % of MMT, 0.22 weight % of FC-430, 0.080 weight% of SD-A, 0.060 weight% of SD-B, and 0.020 weight % of SD-C in 19:1 dichloromethane/methanol. The solution was extrusion dye coated onto a 50 µm Mylar® base sheet at a speed of about 31 ft/min (15 cm/sec) using a web coater. The solvent was evaporated by passing the coated film through a three zone drier. The first zone was at 120°F (49°C), the second at 140°F (60°C), and the third at 160°F (71°C). A coversheet of 23 micron Mylar® (polyethylene terephthalate film) was laminated to the coating as it exited the drier. Dry coating thickness was 20 µm.

The coversheet was removed from the photopolymer and the tacky photopolymer was laminated to 100mmx125mmx3.2mm float glass. Excess film was trimmed away so that the laminated film fit within the edges of the glass substrate. The base sheet was left in place during subsequent processing. We refer to the structure of base/holographic photopolymer and glass plate as the imaging plate. The film side of the imaging plate was coupled to an anti-reflection (AR) plate using Isopar® L (Exxon) to provide a good match of the refractive index of the film to the AR plate. On the opposite side of the imaging plate, a front-surface aluminum mirror was coupled to the surface using the same index matching fluid. Pressure was applied to the stack of plates to provide thin, even index matching fluid layers. The stack of plates was then mounted in a conventional plate

holder mounted on an imaging stage and allowed to settle for more than 30 seconds.

An argon ion laser with emissions at 458nm, a dye laser with emissions at 576nm and a krypton ion laser with emissions at 647nm were combined by appropriate dichroic mirrors in the conventional way to form a 3-color laser beam. This 3-color beam was passed through achromatic optics to form an expanded, collimated, 3-color beam. A shutter was installed to allow each color to be introduced separately. The imaging plate was rotated on the imaging stage such that the 3-color laser beam direction was perpendicular to the imaging stack.

Four holographic mirrors at each imaging wavelength were formed by exposing with a collimated single-color laser beam oriented perpendicular to the film plane and passing, in order, through the anti-reflection plate, Isopar® L layer, base sheet, holographic photopolymer, glass plate and Isopar® L layer and then reflecting back onto itself off the mirror. The exposure energy of holographic mirrors imaged at 647nm was 35.4 mJ/cm^2. The exposure energy of holographic mirrors imaged at 576nm was 17.7 mJ/cm^2. The exposure energy of holographic mirrors imaged at 458nm was 12.5 mJ/cm^2. Each set of four 20 mm diameter region was formed on the plate using identical imaging conditions. The imaging plate was translated to an unimaged region of the film plate after each exposure and allowed to settle for 30 seconds before a subsequent exposure. After imaging, the AR plates, front surface mirror and Isopar® L layers were removed.

The imaging plate was overall exposed to ultraviolet and visible light from a Theimer-Strahler #5027 mercury-arc lamp (Exposure Systems Corp., Bridgeport, Conn.) mounted in a Douthitt DCOP-X exposure unit (Douthitt Corp., Detroit, Michigan) for 120 sec (about 150 mJ/cm^2). The imaging plate was thermally processed by heating at 120°C for 2 hours in a forced-air convection oven.

The transmission spectra of the holographic mirror was recorded using a standard double-beam spectrophotometer (Perkin-Elmer model Lambda-9) with the sample beam oriented perpendicular to the hologram film plane. The results are shown in Table 2.

TABLE 2

spot #	λmax (nm)	DE (%)
1	648.7	79.6%
2	648.0	74.3%
3	647.2	63.7%
4	647.7	66.9%
5	575.7	94.5%
6	575.8	94.8%
7	576.0	95.3%
8	576.1	95.9%
9	457.5	97.4%
10	457.5	97.5%
11	457.5	97.7%
12	457.5	97.9%

Using the element described in Table 2, we again used the same holographic photopolymer described above coated to a thickness of 20 µm between a 23µm Mylar® cover sheet and 50µm Mylar® base sheet on the pilot coater. The coversheet was removed from the photopolymer and the tacky photopolymer was laminated to a section of 100mmx125mmx3.2mm float glass. Excess film was trimmed away so that the laminated film fit within the edges of the glass substrate. The base sheet was left in place during subsequent processing. We refer to the structure of base/holographic photopolymer and glass plate as the imaging plate. The film side of the imaging plate was coupled to glass side of the patterned holographic photomask using Isopar® L (Exxon) to provide a good

match of the refractive index for all of the layers. The anti-reflection plate was attached coupled to the film side of the patterned holographic photomask. On the opposite side of the imaging plate, a front-surface aluminum mirror was coupled to the surface using the same index matching fluid. Pressure was applied to the stack of plates to provide thin, even index matching fluid layers. The stack of plates was then mounted in a conventional plate holder mounted on an imaging stage and allowed to settle for more than 30 seconds.

An argon ion laser with emissions at 458nm, a dye laser with emissions at 576nm and a krypton ion laser with emissions at 647nm were combined by appropriate dichroic mirrors in the conventional way to form a 3-color laser beam. This 3-color beam was passed through achromatic optics to form an expanded, collimated, 3-color beam. A shutter was installed to allow simultaneous exposure of all three wavelengths. The imaging plate was rotated on the imaging stage such that the 3-color laser beam direction was perpendicular to the imaging stack.

Twelve holographic mirrors at each imaging wavelength were formed by exposing with a collimated single-color laser beam oriented perpendicular to the film plane and passing, in order, through the anti-reflection plate, Isopar® L layer, base sheet, holographic photopolymer layer of the patterned holographic photomask, glass plate, Isopar® L layer, base sheet, unexposed holographic photopolymer of imaging plate, glass plate and Isopar® L layer and then reflecting back onto itself off the mirror. The exposure energy of the three-color beam incident upon the patterned holographic photomask was 27 mJ/cm^2 at 647nm, 13.5 mJ/cm^2 at 576nm and 9.5 mJ/cm^2 at 458nm. Each set of four 20 mm diameter regions was formed on the plate using identical imaging conditions. The imaging plate was translated to align with the imaged areas of the

patterned holographic photomask and an unimaged region of the film plate after each exposure and allowed to settle for 30 seconds before a subsequent exposure. After imaging, the AR plates, front surface mirror and Isopar® L layers were removed.

The imaging plate was overall exposed to ultraviolet and visible light from a Theimer-Strahler #5027 mercury-arc lamp (Exposure Systems Corp., Bridgeport, Conn.) mounted in a Douthitt DCOP-X exposure unit (Douthitt Corp., Detroit, Michigan) for 120 sec (about 150 mJ/cm^2). The imaging plate was thermally processed by heating at 120°C for 2 hours in a forced-air convection oven.

The transmission spectra of the holographic mirror was recorded using a standard double-beam spectrophotometer (Perkin-Elmer model Lambda-9) with the sample beam oriented perpendicular to the hologram film plane. The results are shown in Table 3. Spots 1 through 4 should show high diffraction efficiency at 562nm and 446nn and low efficiency at 633nm. While there is a measureable diffraction efficiency at 633nm, we attribute this to the somewhat low diffraction efficiency of the patterned holographic photomask at this wavelength as shown in Table 2 spots 1 through 4. Spots 5 through 8 should show high diffraction efficiency at 633nm and 446nm and low diffraction efficiency at 563nm. This is clearly demonstrated. Spots 9 through 12 should show high diffraction efficiency at 633nm and 563nm and no diffraction efficiency at 446nm. Again, this condition is clearly evident.

TABLE 3

spot #	λmax (nm)	DE (%)	λmax (nm)	DE (%)	λmax (nm)	DE (%)
1	633.2	12.9%	562.2	99.0%	446.9	66.1%
2	633.3	22.4%	562.6	99.7%	447.3	68.4%
3	633.2	35.4%	563.0	99.6%	447.4	66.9%
4	633.5	27.6%	561.2	99.8%	447.8	68.4%
5	632.8	94.0%	563.4	8.8%	447.3	98.9%
6	632.8	92.8%	563.2	6.7%	447.3	98.2%
7	633.0	94.8%	563.0	6.7%	447.4	98.8%
8	633.0	93.7%	-	0.0%	447.5	98.8%
9	633.3	85.5%	562.8	99.7%	-	0%
10	633.7	84.2%	562.6	99.7%	-	0%
11	633.9	82.2%	562.9	99.8%	-	0%
12	634.0	85.2%	562.9	99.8%	-	0%

IV. Generic Description

In a broader sense, each one of the volume holographic optical elements disclosed herein can also be described as a volume holographic optical element comprising a photohardened holographic recording film element. The photohardened holographic recording film element comprises at least a first plurality of pixel volumes and a second plurality of pixel volumes. For certain uses such as in LCD apparatuses, the first pixel volumes and the second pixel volumes are arranged in rows and columns. Each one of the first pixel volumes includes a volume holographic mirror that passes light with at least one first color (e.g., Red) wavelength band and reflects light with at least another color (e.g., Green) wavelength band. Each one of the second pixel volumes includes a volume holographic mirror that passes light with at least the another color (e.g., Green) wavelength band and reflects light with at least the one color (e.g., Red) wavelength band.

Those skilled in the art, having the benefit of the teachings of the present invention as hereinabove set forth, can effect numerous modifications thereto. These modifications are to be construed as being encompassed within the scope of the present invention as set forth in the appended claims.

CLAIMS

What is claimed is:

1. A volume holographic optical element, comprising:

a photohardened holographic recording film element comprising at least a first plurality of pixel volumes and a second plurality of pixel volumes arranged in rows and columns;

each one of the first pixel volumes including a volume holographic mirror that passes light with at least one first color (e.g., Red) wavelength band and reflects light with at least another color (e.g., Green) wavelength band; and

each one of the second pixel volumes including a volume holographic mirror that passes light with at least the another color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band.

2. In a liquid crystal display apparatus having a multicolor filter comprising (i) at least a first plurality of pixel volumes that pass light with at least a first color (e.g., Red) wavelength band and block light with at least a second color (e.g., Green) wavelength band and (ii) a second plurality of pixel volumes that passes light with at least a second color (e.g., Green) wavelength band and blocks light with at least the first color (e.g., Red) wavelength band, wherein the improvement comprises the filter being a photohardened holographic recording film element.

3. A volume holographic optical element, comprising:

a photohardened holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that reflects light with a first color (e.g., Red) wavelength band and passes light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that reflects light with the second color (e.g., Green) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that reflects light with the third color (e.g., Blue) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

4. The element of Claim 3, wherein the first color (e.g., Red) wavelength band has a width of at least 5 nanometers and includes 612 nanometer, the second color (e.g., Green) wavelength band has a width of at least 5 nanometers and includes 545 nanometer, and the third color (e.g., Blue) wavelength band has a width of at least 5 nanometers and includes 436 nanometer.

5. The element of Claim 3, wherein the film element comprises a single photohardened holographic recording film layer.

6. The element of Claim 3, wherein the film element comprises two photohardened holographic recording film layers.

7. The element of Claim 3, wherein the film element comprises three photohardened holographic recording film layers.

8. In a reflective liquid crystal display apparatus, comprising, in order,:

a first light polarizer for passing ambient light having a first polarization;

a liquid crystal display element for selectively modifying the polarization of the light passing through an array of cells such that the polarization of light passing through a first set, a second set or a third set of the cells can be changed to a second polarization;

a second light polarizer for passing light from the liquid crystal display element having the second polarization; and

a holographic multicolor reflection filter comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that reflects light with a first color (e.g., Red) wavelength band and passes light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that reflects light with the second color (e.g., Green) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that reflects light with the third color (e.g., Blue) wavelength band and passes light with at least the first color

(e.g., Red) wavelength band and the second color (e.g., Green) wavelength band;

such that (1) when the liquid crystal display element modifies the polarization of the light passing through the first set of cells to the second polarization, the light passes through the second polarizer into the first pixel volumes in which the first volume holographic mirrors reflect light with the first color (e.g., Red) wavelength band back to a viewer, (2) when the liquid crystal display element modifies the polarization of the light passing through the second set of cells to the second polarization, the light passes through the second polarizer into the second pixel volumes in which the second volume holographic mirrors reflect light with the second color (e.g., Green) wavelength band back to the viewer, and (3) when the liquid crystal display element modifies the polarization of the light passing through the third set of cells to the second polarization, the light passes through the third polarizer into the third pixel volumes in which the third volume holographic mirrors reflect light with the third color (e.g., Blue) wavelength band back to the viewer.

9. A method for making a first volume holographic optical element, comprising:

a holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that reflects light with a first color (e.g., Red) wavelength band and passes light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that reflects light with

the second color (e.g., Green) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that reflects light with the third color (e.g., Blue) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band; the method comprising:

(A) holographically exposing the film element with coherent or substantially coherent light to record the first volume holographic mirrors in the first pixel volumes;

(B) holographically exposing the film element with coherent or substantially coherent light to record the second volume holographic mirrors in the second pixel volumes; and

(C) holographically exposing the film element with coherent or substantially coherent light to record the third volume holographic mirrors in the third pixel volumes.

10. The method of Claim 9, wherein steps (A), (B) and (C) are performed simultaneously.

11. The method of Claim 9, wherein the step (A) comprises:

directing coherent or substantially coherent light through a photomask having a first plurality of pixels which block light and a second plurality of pixels which allow light to pass and then through the film element onto a reflector which reflects the coherent or substantially coherent light back through the film element holographically forming the first volume holographic mirrors in the first pixel volumes.

12. The method of Claim 11, further comprising:

before step (A), positioning a first index matching fluid layer on the reflector, a glass support on the first index matching fluid layer, the film element on the glass support, a second index matching fluid layer on the film element, the photomask on the second index matching fluid layer, and an anti-reflection layer on the photomask.

13. The method of Claim 11, wherein the step (B) is after step (A) and comprises:

shifting the photomask one pixel in a first direction; and

directing coherent or substantially coherent light through the photomask and then the film element onto the reflector which reflects the coherent or substantially coherent light back through the film element holographically forming the second volume holographic mirrors in the second pixel volumes.

14. The method of Claim 13, wherein the step (C) is after step (B) and comprises:

shifting the photomask one pixel in the first direction; and

directing coherent or substantially coherent light through the photomask and then the film element onto the reflector which reflects the coherent or substantially coherent light back through the film element holographically forming the third volume holographic mirrors in the third pixel volumes.

15. The method of Claim 9, further comprising curing the holographic recording film element by exposing it to actinic radiation to substantially polymerize any monomer and fix the holographic mirrors in the film element.

16. The method of Claim 9, further comprising heating the holographic recording film to increase the refractive index modulation, efficiency and bandwidth of the holographic mirrors.

17. The method of Claim 9, further comprising forming the film element with a single, substantially solid, holographic recording film.

18. A volume holographic optical element, comprising:

a photohardened holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

19. The element of Claim 18, wherein the first color (e.g., Red) wavelength band has a width of at least 5 nanometers and includes 612 nanometer, the second color (e.g., Green) wavelength band has a width of at least 5

nanometers and includes 545 nanometer, and the third color (e.g., Blue) wavelength band has a width of at least 5 nanometers and includes 436 nanometer.

20. The element of Claim 18, wherein the film element comprises a single photohardened holographic recording film.

21. The element of Claim 18, wherein:

the film element comprising a first holographic recording layer, a second holographic recording layer, and a third holographic recording layer;

each one of the first pixel volumes, the second pixel volumes and the third pixel volumes comprises a first layer volume, a second layer volume and a third layer volume;

each of the first volume holographic mirrors comprising:

a fourth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band and reflects light with the third color (e.g., Blue) wavelength band, the fourth mirrors in the third layer volumes of the first pixel volumes; and

a fifth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the second color (e.g., Green) wavelength band, the fifth mirrors in the second layer volumes of the first pixel volumes; and

each of the second volume holographic mirrors comprising:

one of the fourth mirrors in the third layer volumes of the second pixel volumes; and

a sixth volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the first color (e.g., Red) wavelength band, the sixth mirrors in the first layer volumes of the second pixel volumes; and

each of the third volume holographic mirrors comprising:

one of the fifth mirrors in the second layer volumes of the third pixel volumes; and

one of the sixth mirrors in the first layer volumes of the third pixel volumes.

22. The element of Claim 18, wherein:

the film element comprising a first holographic recording layer and a second holographic recording layer on the first layer;

each one of the first pixel volumes, the second pixel volumes and the third pixel volumes comprises a first layer volume and a second layer volume;

each of the first volume holographic mirrors comprising:

a fourth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band and reflects light with the third color (e.g., Blue) wavelength band, the fourth mirrors in the first layer volumes of the first pixel volumes; and

a fifth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the second color (e.g., Green) wavelength band, the fifth mirrors in the second layer volumes of the first pixel volumes; and

each of the second volume holographic mirrors comprising:

one of the fourth mirrors in the second layer volumes of the second pixel volumes; and

a sixth volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the first color (e.g., Red) wavelength band, the sixth mirrors in the first layer volumes of the second pixel volumes; and

each of the third volume holographic mirrors comprising:

one of the fifth mirrors in the second layer volumes of the third pixel volumes; and

one of the sixth mirrors in the first layer volumes of the third pixel volumes.

23. In a transmission liquid crystal display apparatus, comprising, in order,:

a light assembly which emits light with a first color (e.g., Red) wavelength band, a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

a first light polarizer for passing light from the light assembly having a first polarization;

a liquid crystal display element for selectively modifying the polarization of the light passing through an array of cells such that the polarization of light passing through a first set, a second set or a third set of the cells can be changed to a second polarization;

a holographic multicolor transmission filter comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light

with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band;

a second light polarizer for passing light having a second polarization,

such that (1) when the liquid crystal display element modifies the polarization of the light passing through the first set of cells to the second polarization, the light passes into the first pixel volumes in which the first volume holographic mirrors pass light with the first color (e.g., Red) wavelength band through the second polarizer to a viewer, (2) when the liquid crystal display element modifies the polarization of the light passing through the second set of cells to the second polarization, the light passes into the second pixel volumes in which the second volume holographic mirrors pass light with the second color (e.g., Green) wavelength band through the second polarizer to the viewer, and (3) when the liquid crystal display element modifies the polarization of the light passing through the third set of cells to the second polarization, the light passes into the third pixel volumes in which the third volume holographic mirrors

pass light with the third color (e.g., Blue) wavelength band through the third polarizer to the viewer.

24. A method for making a second volume holographic optical element from a first volume holographic optical element, the first volume holographic optical element comprising:

a first holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that reflects light with a first color (e.g., Red) wavelength band and passes light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that reflects light with the second color (e.g., Green) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that reflects light with the third color (e.g., Blue) wavelength band and passes light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band;

the method comprising:

directing coherent or substantially coherent light including the first color (e.g., Red) wavelength band, the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band through the first volume holographic optical element and then a second holographic recording film element;

reflecting the coherent or substantially coherent light off a reflector back through the second film element; and

holographically forming the second volume holographic optical element comprising:

the second film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band.

25. The method of Claim 24, further comprising:

before the directing step, positioning the second film element on the reflector, a glass support on the second film element, and the first film element on the glass support.

26. The method of Claim 24, further comprising;

removing the first film element; and

curing the second film element by exposing it to actinic radiation to substantially polymerize any monomer and fix the holographic mirrors in the second film element.

27. The method of Claim 26, further comprising, after the removing step and before the curing step, laminating a cover sheet to the second film element.

28. The method of Claim 27, further comprising heating the second film element to increase the refractive index modulation, efficiency and bandwidth of the holographic mirrors.

29. The method of Claim 27, further comprising:

removing the reflector; and

laminating the second film element to a second glass support.

30. The method of Claim 24, further comprising forming the film element with a single, substantially solid, holographic recording film.

31. The method of Claim 24, forming the film element with a first holographic recording layer sensitized to the third color (e.g., Blue) wavelength band, a second holographic recording layer sensitized to the second color (e.g., Green) wavelength band on the first layer, and a third holographic recording layer sensitized to the first color (e.g., Red) wavelength band on the second layer.

32. A method for making a second volume holographic optical element from a first volume holographic optical element, comprising:

a first holographic recording film element comprising a first plurality of pixel volumes, a

second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band;

the method comprising:

directing coherent or substantially coherent light including the first color (e.g., Red) wavelength band, the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band through a laminate comprising a second holographic recording film element and then the first volume holographic optical element;

reflecting the second color wavelength band and the third color wavelength band off the first mirrors back through first pixel volumes of the second film element;

reflecting the first color wavelength band and the third color wavelength band off the second mirrors back through second pixel volumes of the second film element;

reflecting the first color wavelength band and the second color wavelength band off the third mirrors back

through third pixel volumes of the second film element; and

holographically forming the second volume holographic optical element.

33. The method of Claim 32, further comprising:

before the directing step, positioning the first film element on a light absorbing layer, a glass support on the first film element, the first film element on the glass support, an index matching fluid layer on the first film element, and an anti-reflection layer on the index matching fluid layer.

34. The method of Claim 33, further comprising;

removing the light absorbing layer, the first film element, the glass support, the index matching fluid layer and the anti-reflection layer; and

curing the second film element by exposing it to actinic radiation to substantially polymerize any monomer and fix the holographic mirrors in the second film element.

35. The method of Claim 34, further comprising heating the second film element to increase the refractive index modulation, efficiency and bandwidth of the holographic mirrors.

36. The method of Claim 35, further comprising laminating the second film element to a second glass support.

37. The method of Claim 32, further comprising forming the film element with a single, substantially solid, holographic recording film.

38. The method of Claim 32, forming the film element with a first holographic recording layer sensitized to

the third color (e.g., Blue) wavelength band, a second holographic recording layer sensitized to the second color (e.g., Green) wavelength band on the first layer, and a third holographic recording layer sensitized to the first color (e.g., Red) wavelength band on the second layer.

39. A method for making a multi-layer volume holographic optical element, comprising:

a photohardened holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band;

the film element comprising a first holographic recording layer sensitized to the third color (e.g., Blue) wavelength band, a second holographic recording layer sensitized to the second color (e.g., Green) wavelength band on the first layer, and a third

holographic recording layer sensitized to the first color (e.g., Red) wavelength band on the second layer;

each one of the first pixel volumes, the second pixel volumes and the third pixel volumes comprises a first layer volume, a second layer volume and a third layer volume;

each of the first volume holographic mirrors comprising:

a fourth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band and reflects light with the third color (e.g., Blue) wavelength band, the fourth mirrors in the third layer volumes of the first pixel volumes; and

a fifth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the second color (e.g., Green) wavelength band, the fifth mirrors in the second layer volumes of the first pixel volumes; and

each of the second volume holographic mirrors comprising:

one of the fourth mirrors in the third layer volumes of the second pixel volumes; and

a sixth volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the first color (e.g., Red) wavelength band, the sixth mirrors in the first layer volumes of the second pixel volumes; and

each of the third volume holographic mirrors comprising:

one of the fifth mirrors in the second layer volumes of the third pixel volumes; and

one of the sixth mirrors in the first layer volumes of the third pixel volumes;

the method comprising:

imagewise exposing the film element to actinic radiation to polymerize monomer in selected first layer volumes, second layer volumes and third layer volumes to make the exposed volumes holographically inactive; and

holographically imaging the film element with coherent or substantially coherent light consisting essentially of the first color (e.g., Red) wavelength band, the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band to record the multi-layer volume holographic optical element.

40. A method for making a two-layer volume holographic optical element, comprising:

a photohardened holographic recording film element comprising a first plurality of pixel volumes, a second plurality of pixel volumes, and a third plurality of pixel volumes;

each one of the first pixel volumes including a first volume holographic mirror that passes light with a first color (e.g., Red) wavelength band and reflects light with at least a second color (e.g., Green) wavelength band and a third color (e.g., Blue) wavelength band;

each one of the second pixel volumes including a second volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and reflects light with at least the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band; and

each one of the third pixel volumes including a third volume holographic mirror that passes light with the third color (e.g., Blue) wavelength band and reflects light with at least the first color (e.g., Red)

wavelength band and the second color (e.g., Green) wavelength band;

the film element comprising a first holographic recording layer at least sensitized to the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band, and a second holographic recording layer at least sensitized to the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band on the first layer;

each one of the first pixel volumes, the second pixel volumes and the third pixel volumes comprises a first layer volume and a second layer volume;

each of the first volume holographic mirrors comprising:

a fourth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the second color (e.g., Green) wavelength band and reflects light with the third color (e.g., Blue) wavelength band, the fourth mirrors in the first layer volumes of the first pixel volumes; and

a fifth volume holographic mirror that passes light with the first color (e.g., Red) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the second color (e.g., Green) wavelength band, the fifth mirrors in the second layer volumes of the first pixel volumes; and

each of the second volume holographic mirrors comprising:

one of the fourth mirrors in the second layer volumes of the second pixel volumes; and

a sixth volume holographic mirror that passes light with the second color (e.g., Green) wavelength band and the third color (e.g., Blue) wavelength band and reflects light with the first color (e.g., Red) wavelength

band, the sixth mirrors in the first layer volumes of the second pixel volumes; and

each of the third volume holographic mirrors comprising:

one of the fifth mirrors in the second layer volumes of the third pixel volumes; and

one of the sixth mirrors in the first layer volumes of the third pixel volumes;

the method comprising:

imagewise holographically exposing the second layer with coherent or substantially coherent light consisting essentially of the third color (e.g., Blue) wavelength band to record the fourth volume holographic mirrors in the second layer volumes of the second pixel volumes;

imagewise holographically exposing the second layer with coherent or substantially coherent light consisting essentially of the second color (e.g., Green) wavelength band to record the fifth volume holographic mirrors in the second layer volumes of the first pixel volumes and the third pixel volumes;

laminating the first holographic recording layer adjacent the second layer;

imagewise holographically exposing the first layer with coherent or substantially coherent light consisting essentially of the third color (e.g., Blue) wavelength band to record the fourth volume holographic mirrors in the first layer volumes of the first pixel volumes;

imagewise holographically exposing the first layer with coherent or substantially coherent light consisting essentially of the first color (e.g., Red) wavelength band to record the sixth volume holographic mirrors in the first layer volumes of the second pixel volumes and the third pixel volumes.

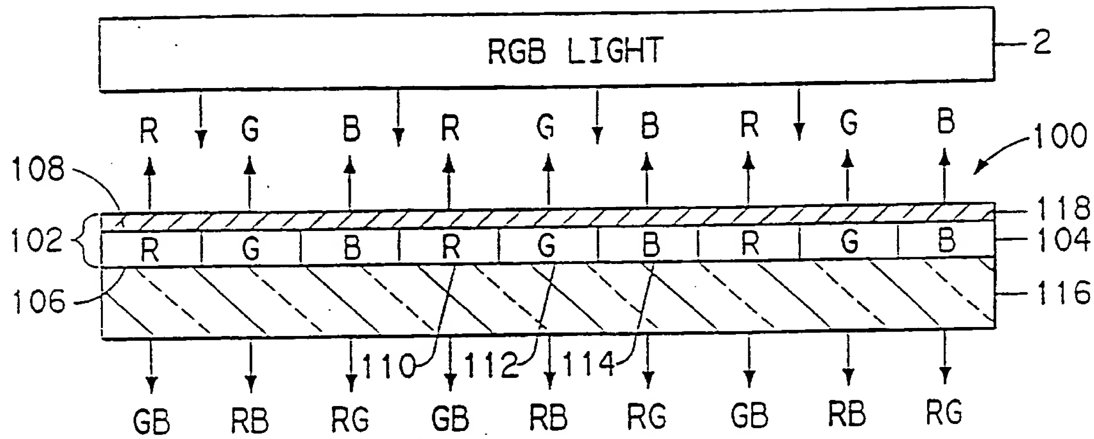

FIG.1

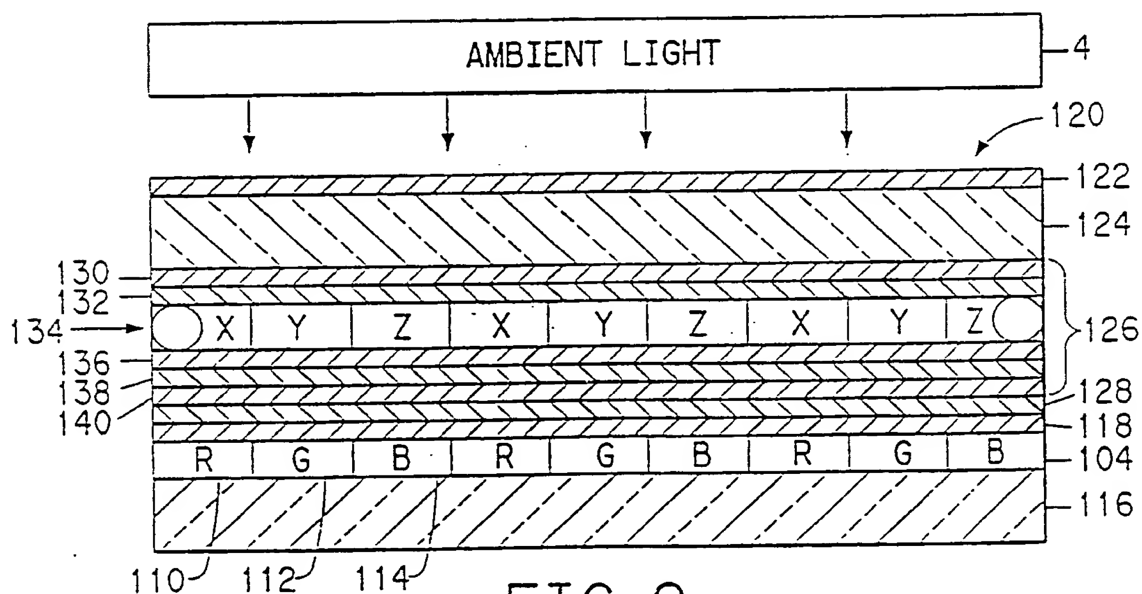

FIG.2

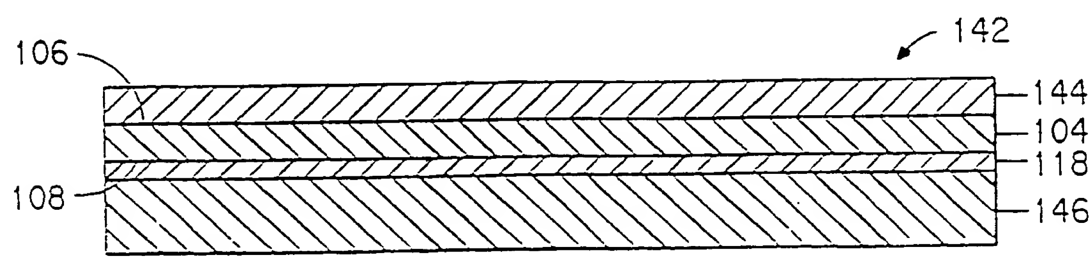

FIG.3

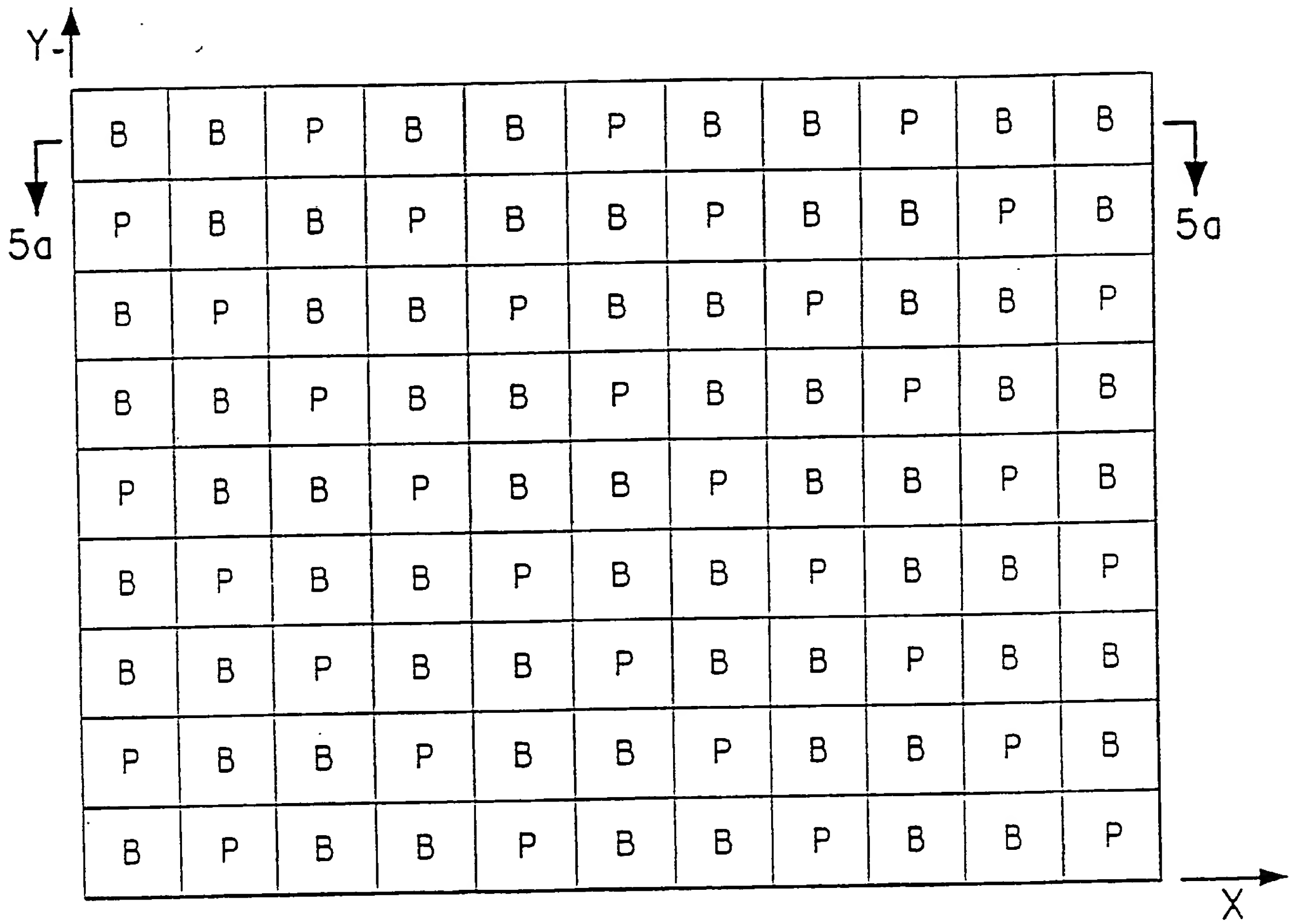
Y
5a
5a
B B P B B P B B P B B
P B B P B B P B B P B
B P B B P B B P B B P
B B P B B P B B P B B
P B B P B B P B B P B
B P B B P B B P B B P
B B P B B P B B P B B
P B B P B B P B B P B
B P B B P B B P B B P
X

FIG.4

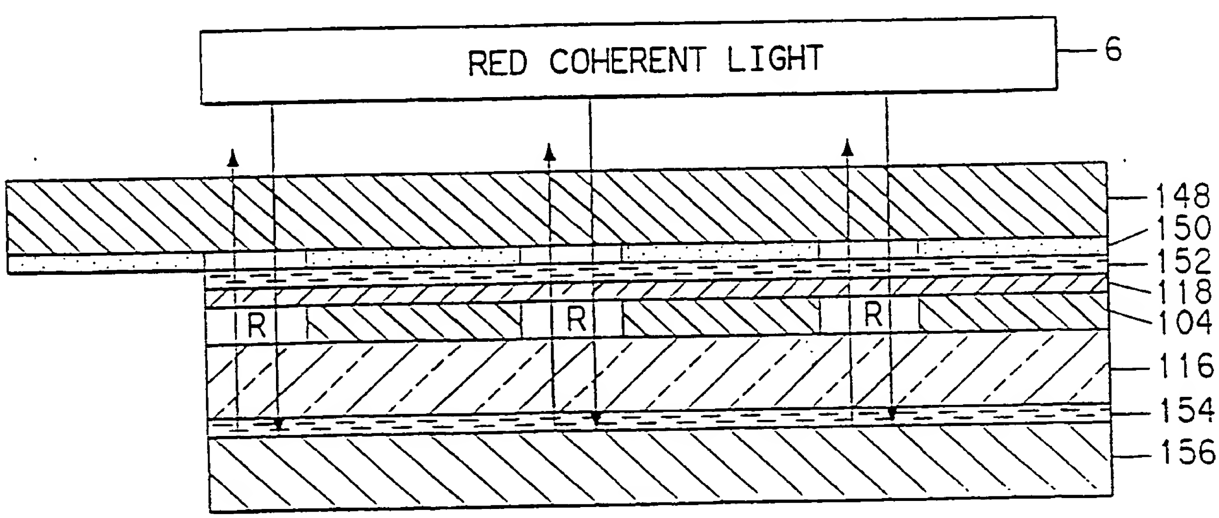
RED COHERENT LIGHT
6
R
R
R
148
150
152
118
104'
116
154
156

FIG.5a

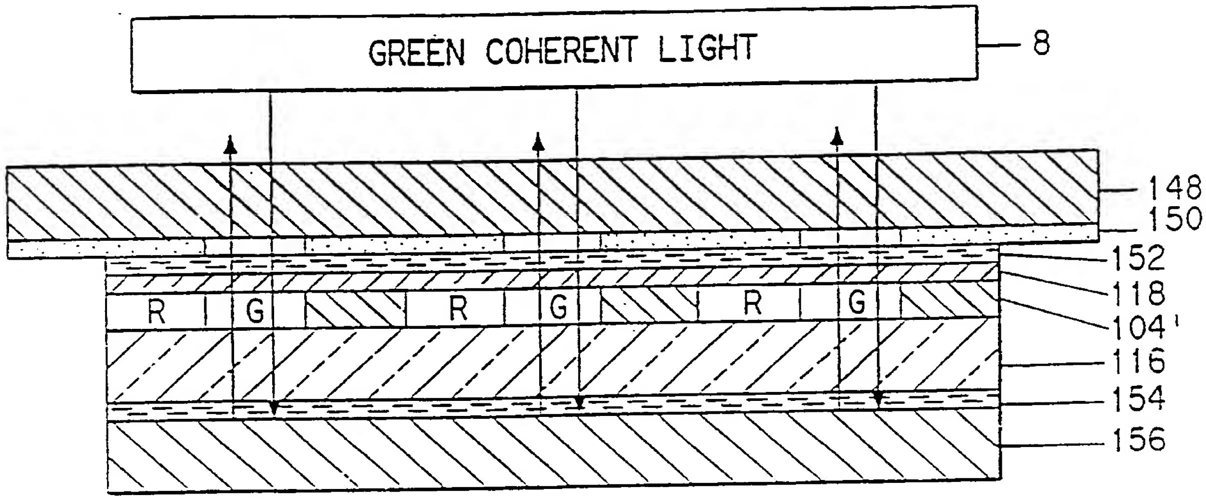
GREEN COHERENT LIGHT
8
148
150
152
118
104'
116
154
156
R
G
R
G
R
G

FIG.5b

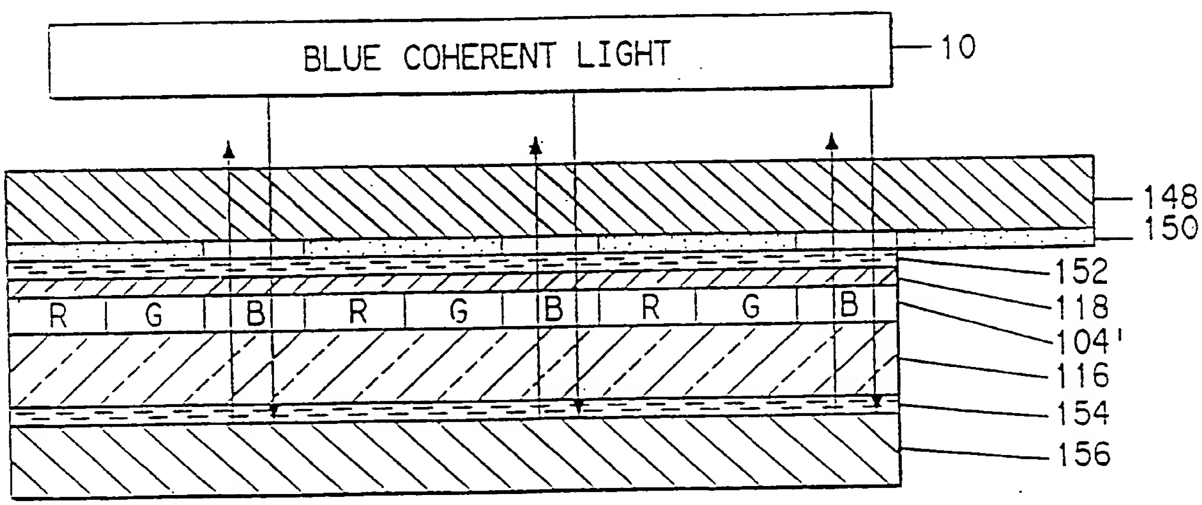
BLUE COHERENT LIGHT
10
148
150
152
118
104'
116
154
156
R
G
B
R
G
B
R
G
B

FIG.5c

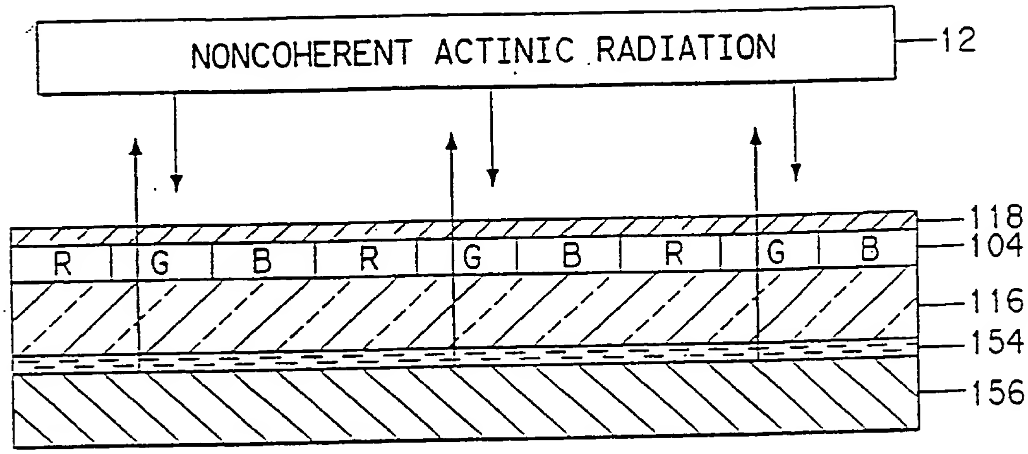

FIG.5d

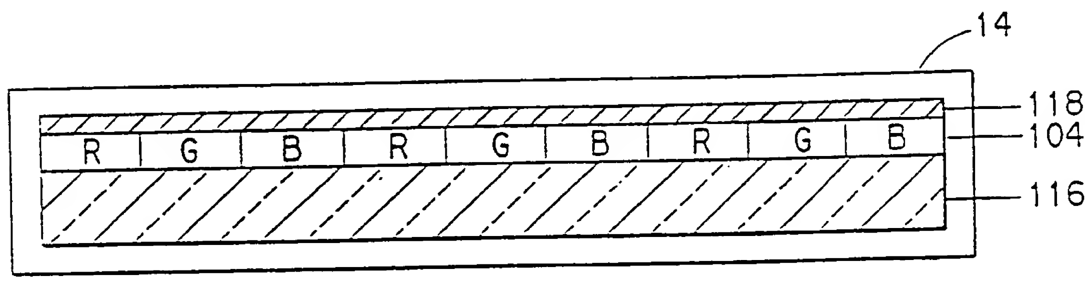

FIG.5e

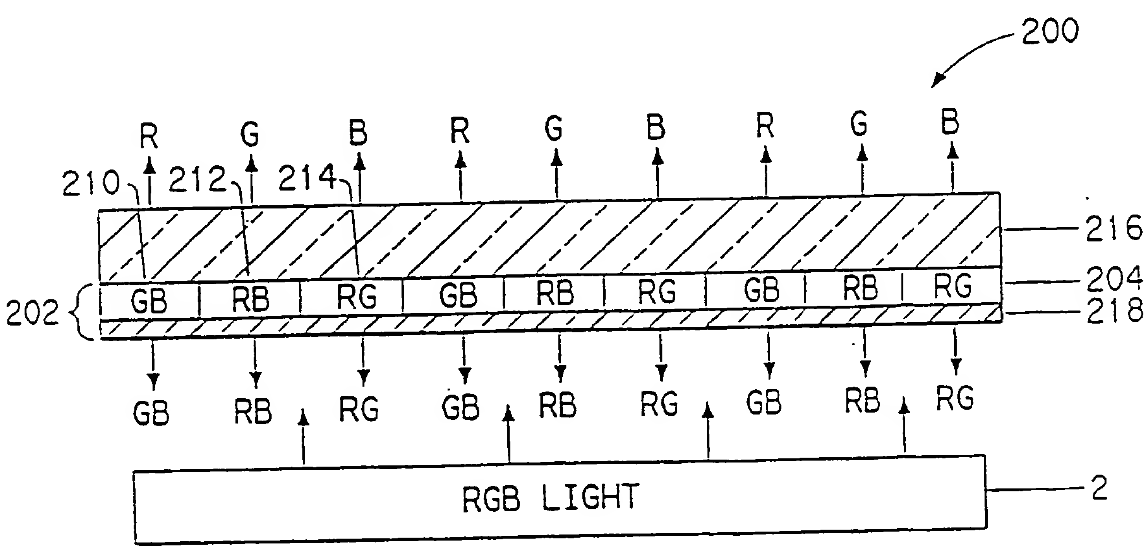

FIG.6

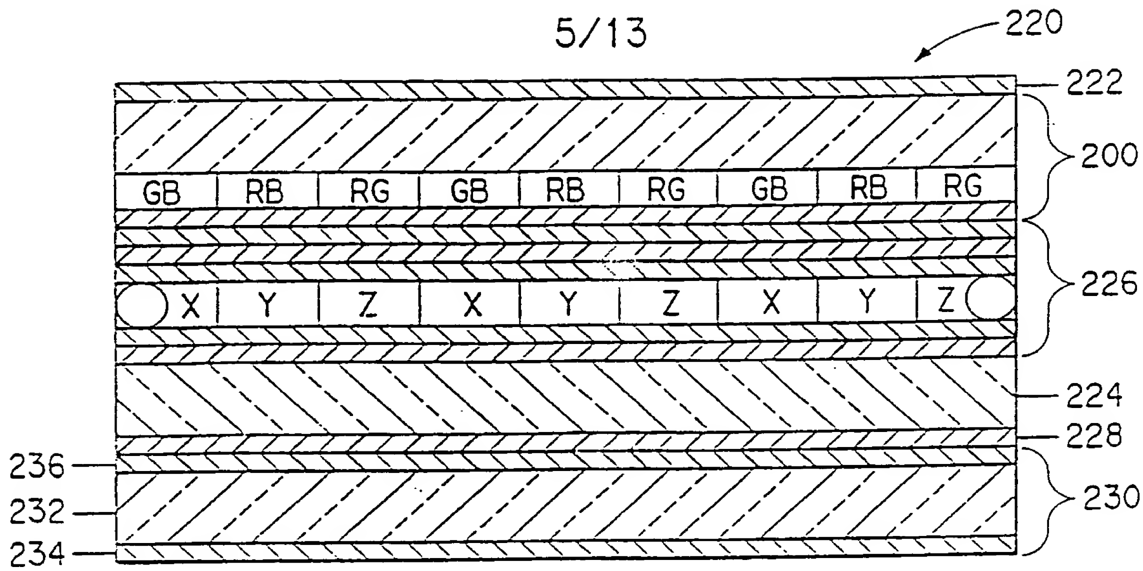
220
222
200
GB
RB
RG
GB
RB
RG
GB
RB
RG
226
X
Y
Z
X
Y
Z
X
Y
Z
224
228
236
232
234
230

FIG.7a

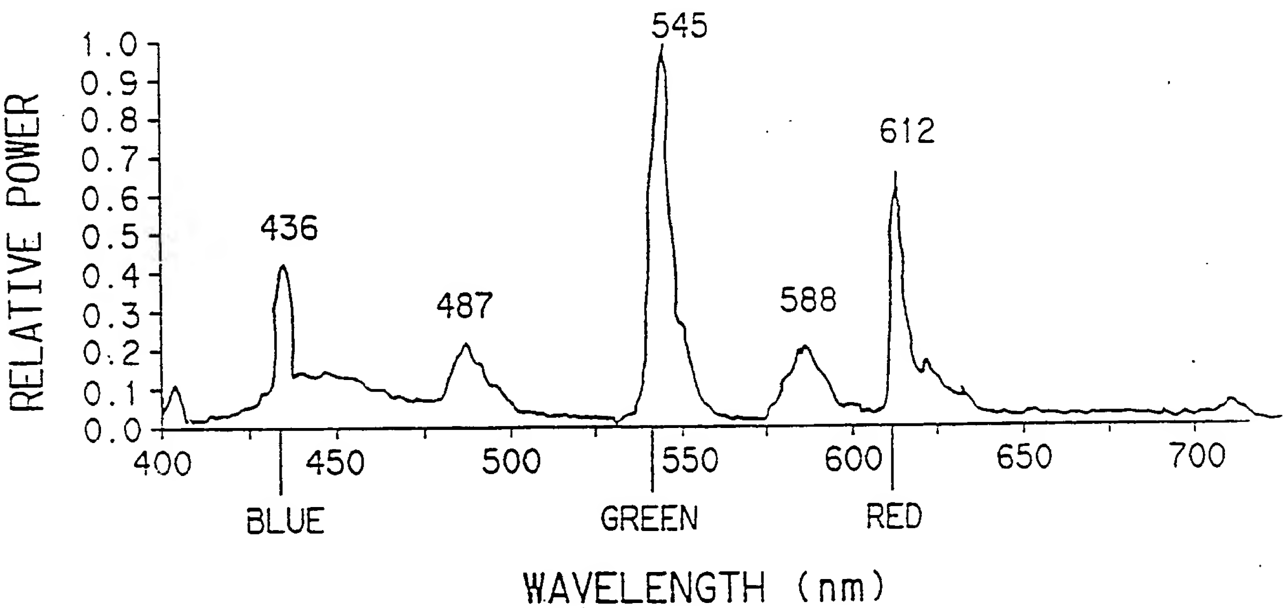
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
RELATIVE POWER
545
612
436
487
588
400
450
500
550
600
650
700
BLUE
GREEN
RED
WAVELENGTH (nm)

FIG.7B

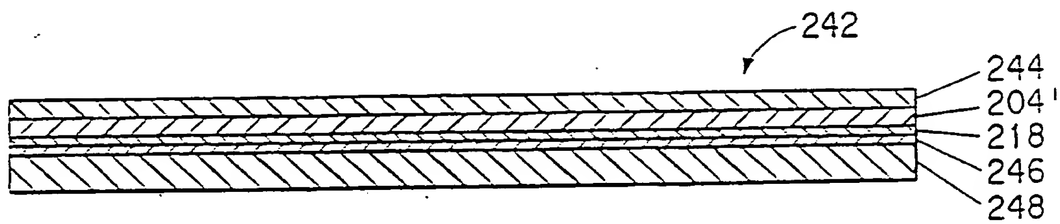

FIG.8

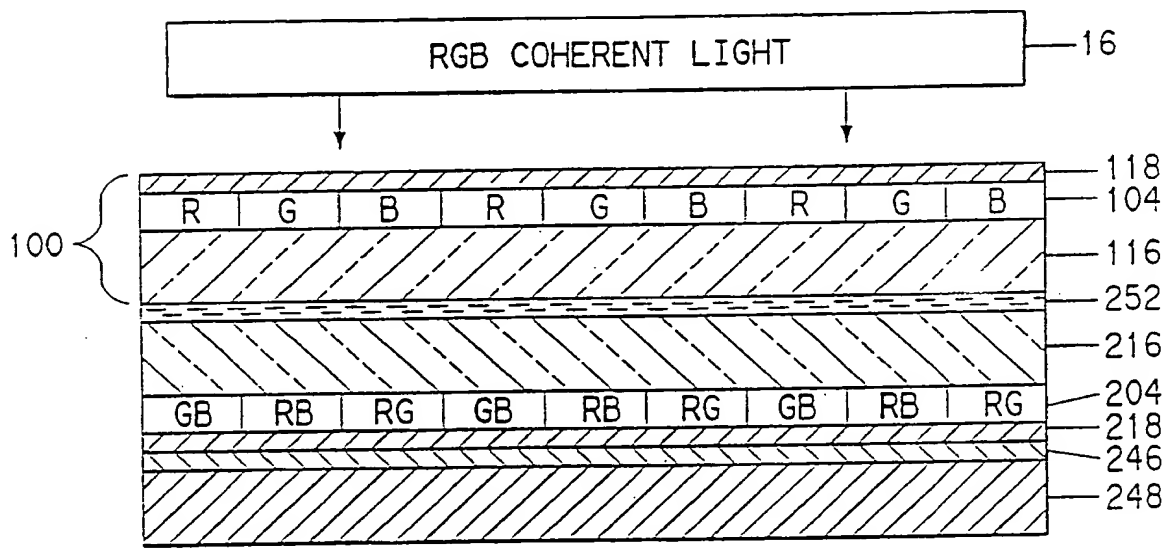

FIG.9a

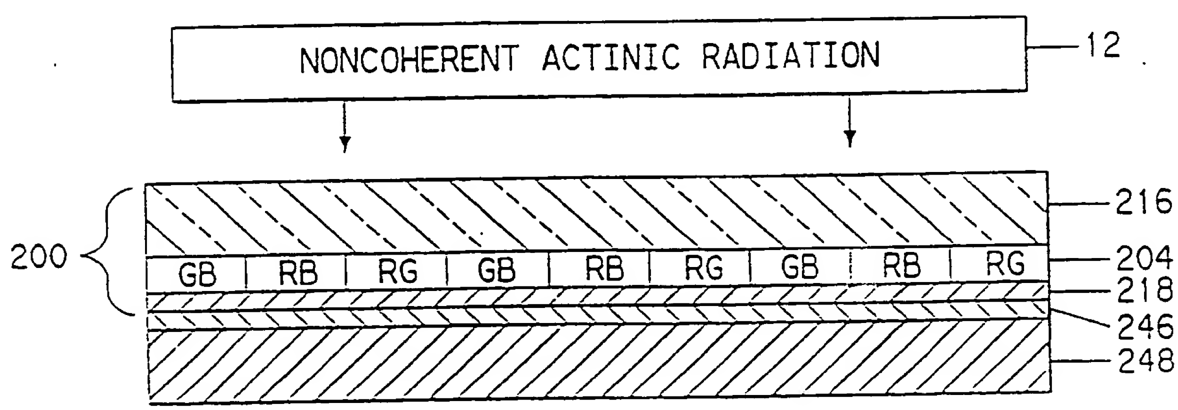

FIG.9b

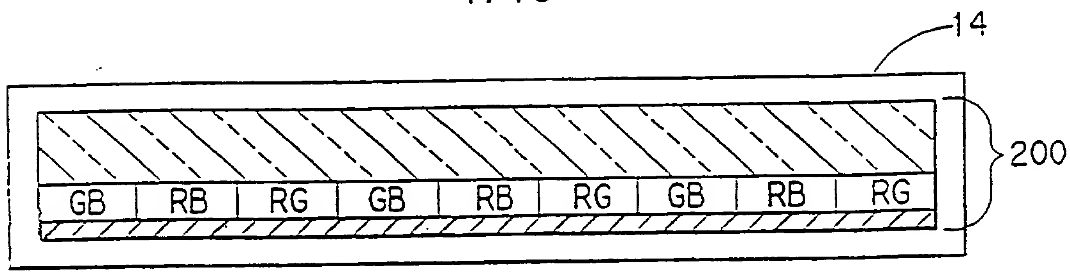

FIG.9c

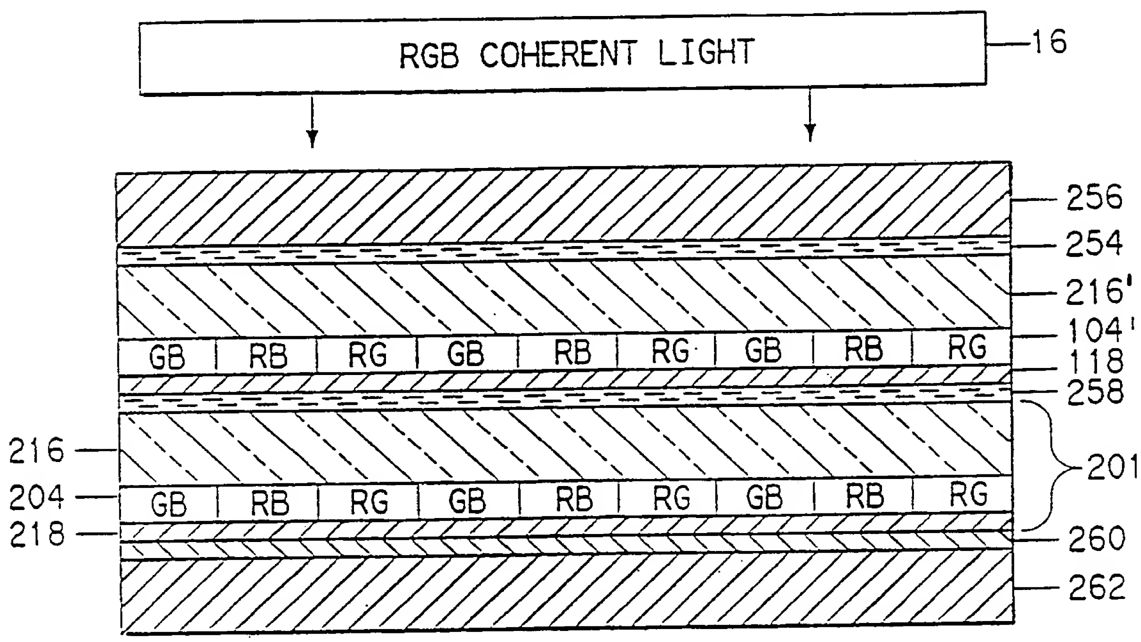

FIG.10a

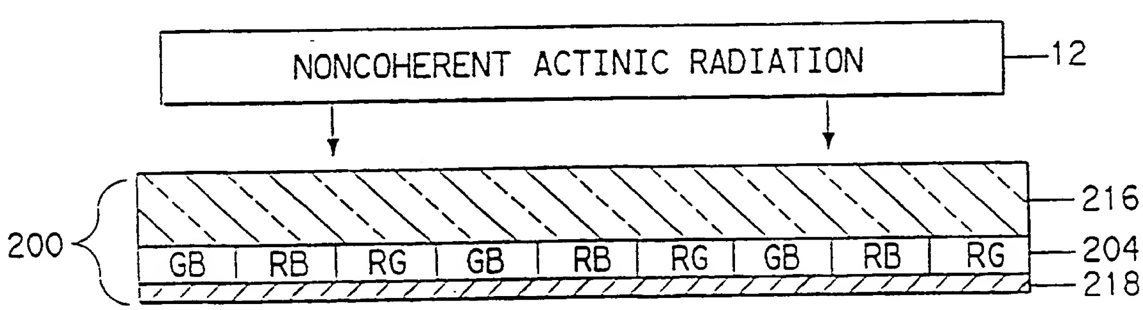

FIG.10b

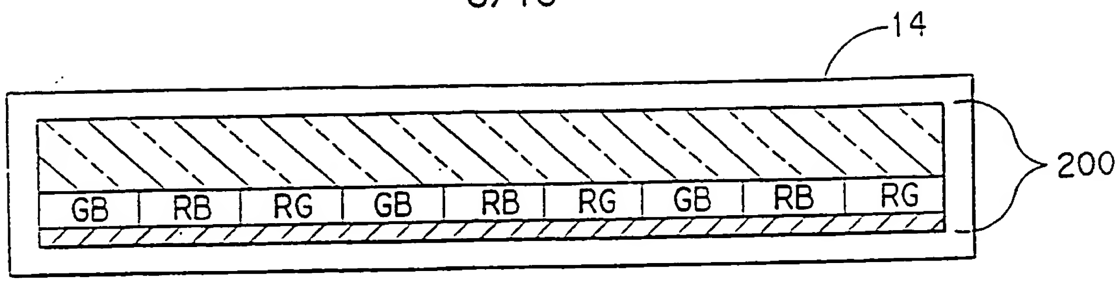

FIG.10c

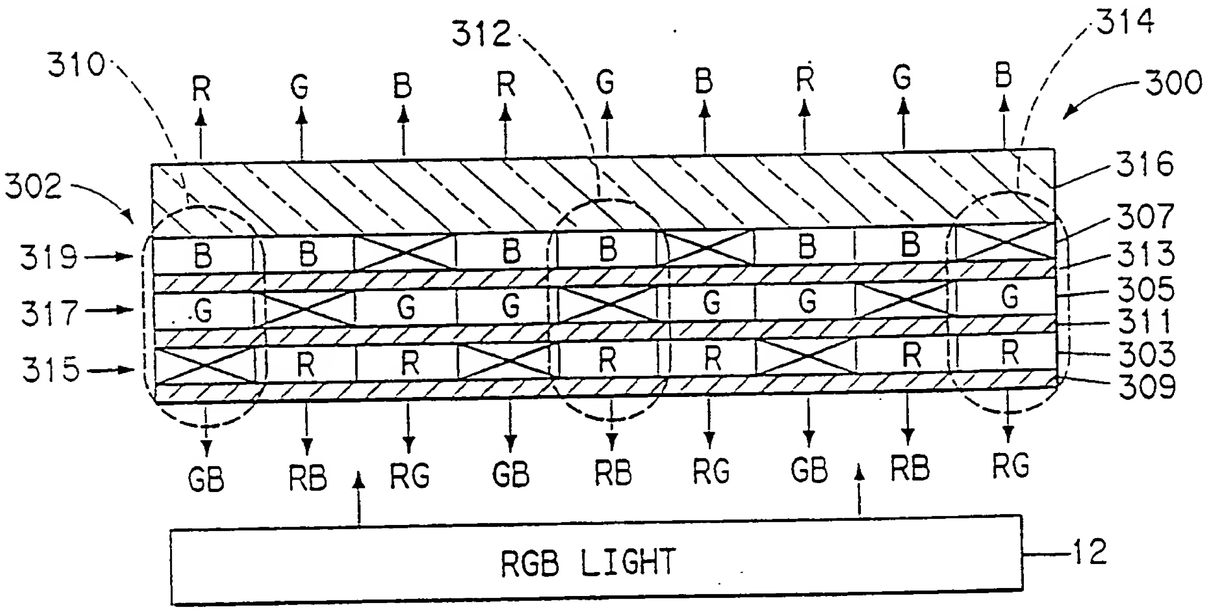

FIG.11

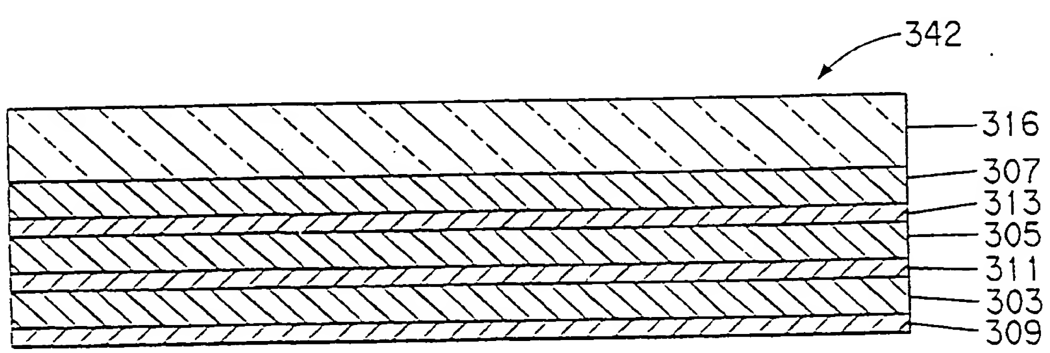

FIG.12

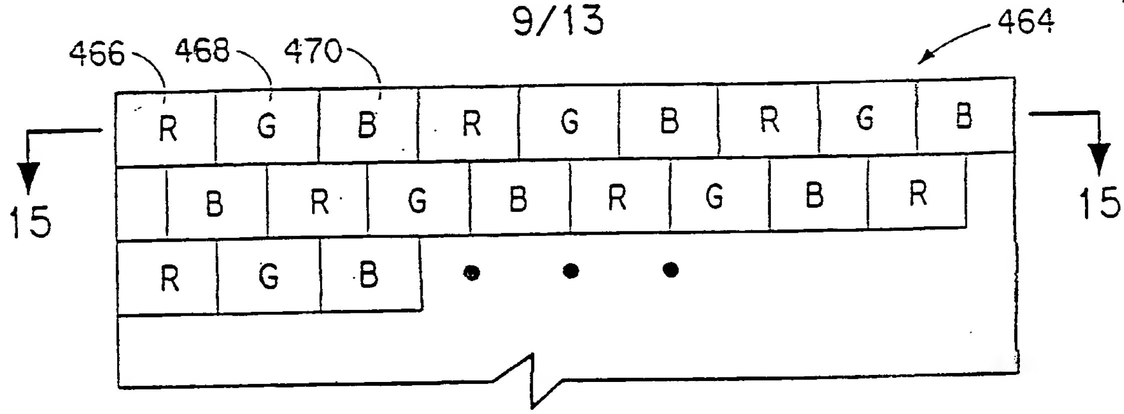

FIG.13a

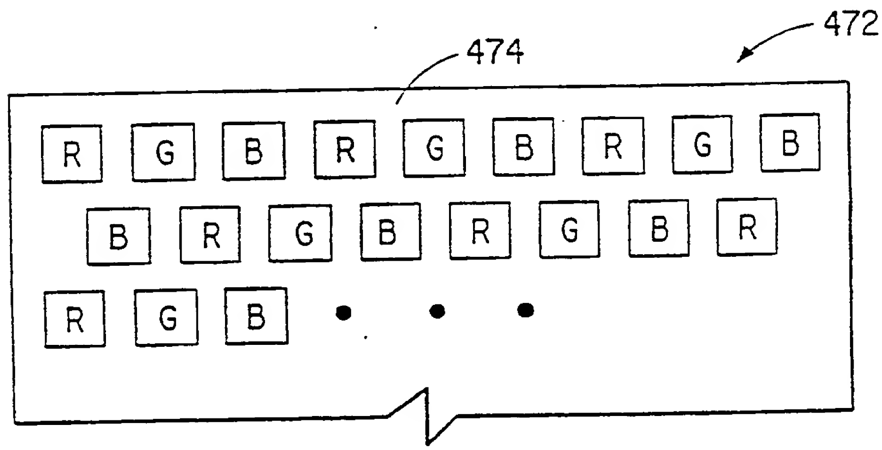

FIG.13b

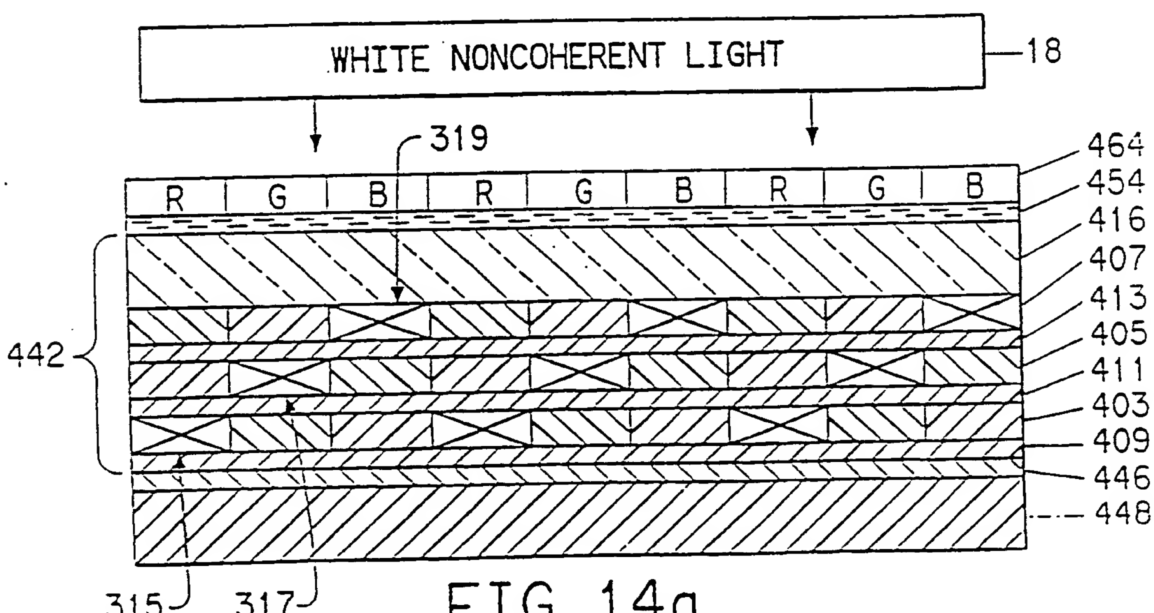

FIG.14a

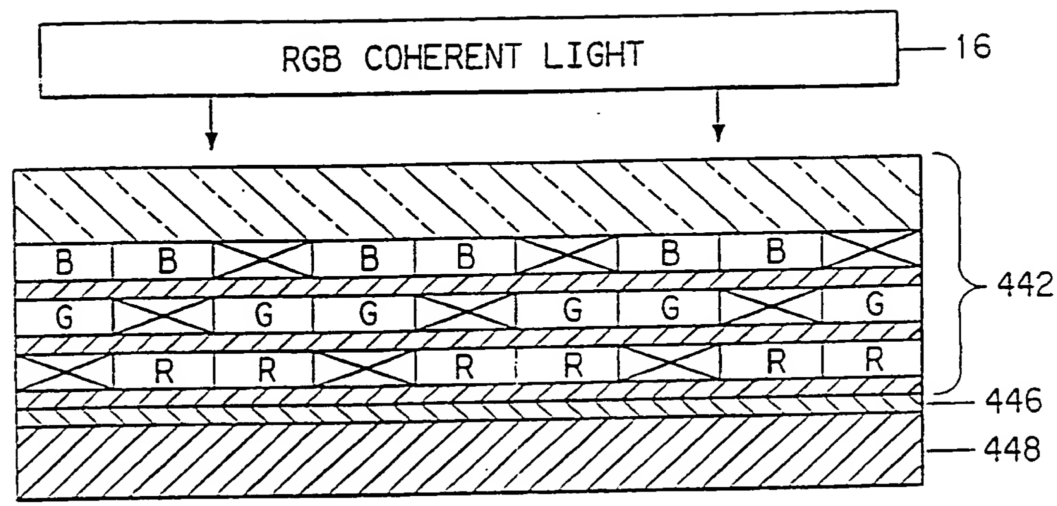

FIG.14b

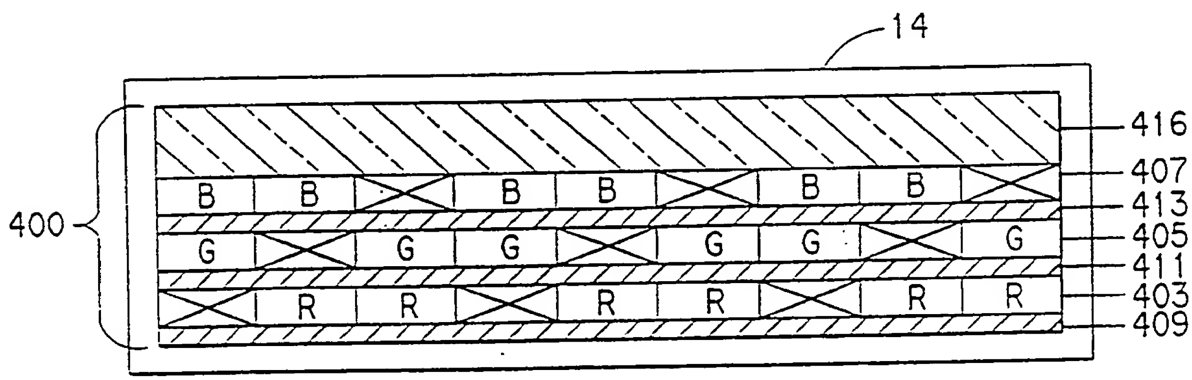

FIG.14c

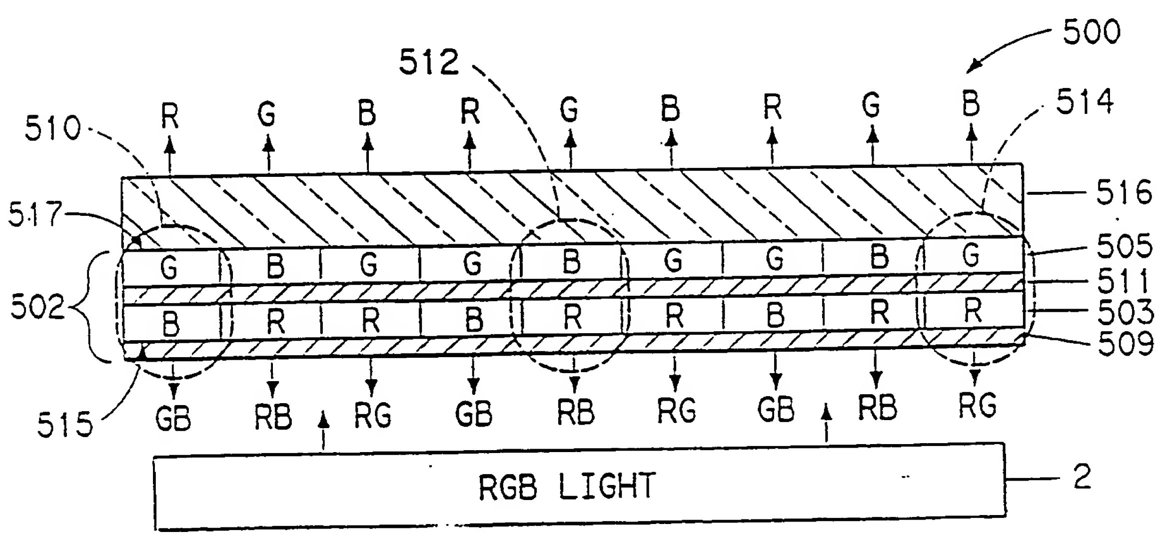

FIG.15

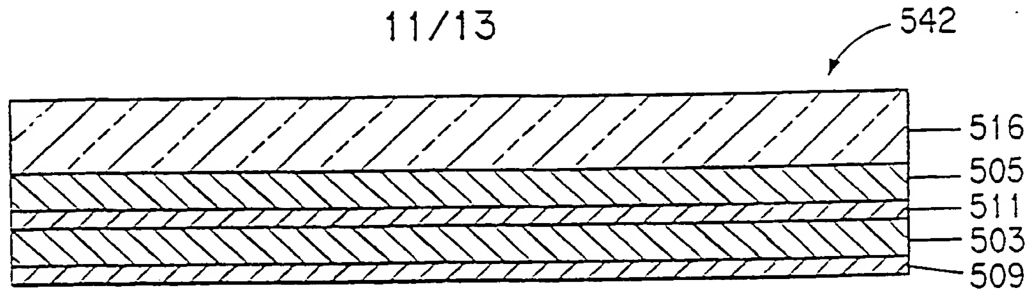

FIG.16

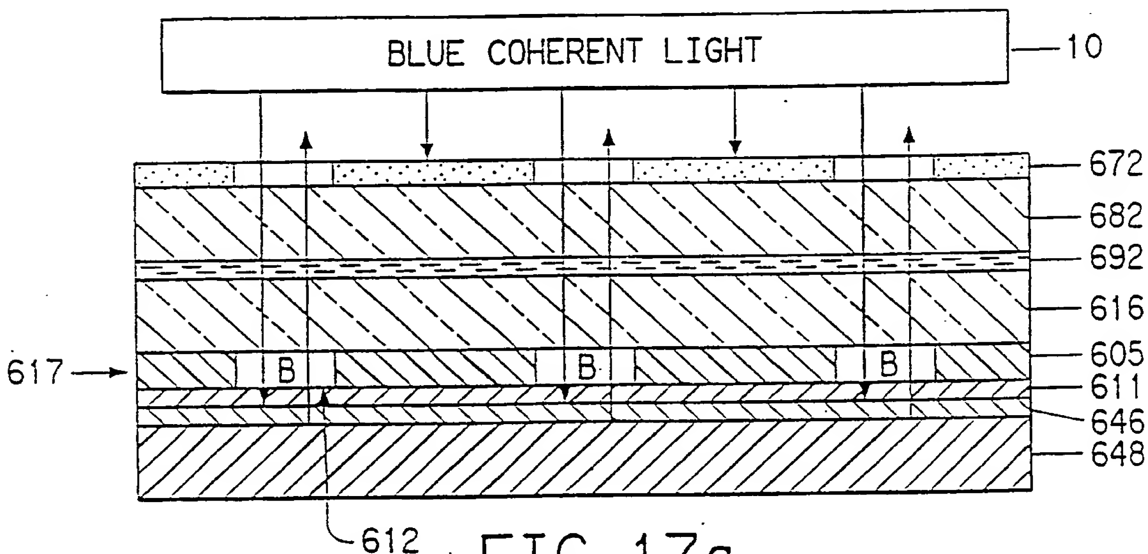

FIG.17a

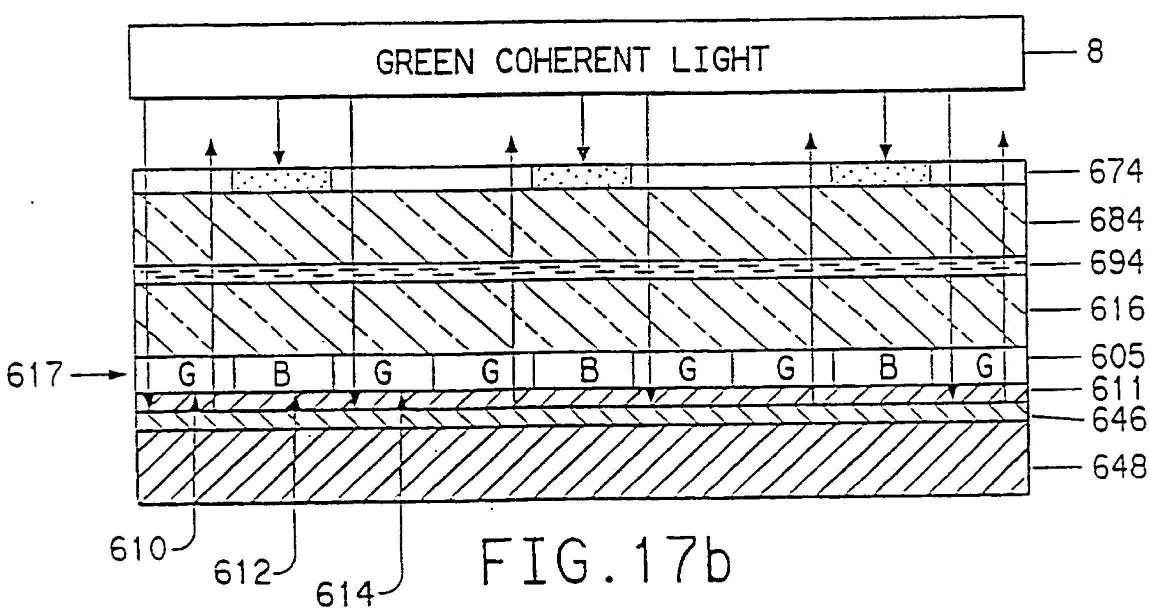

FIG.17b

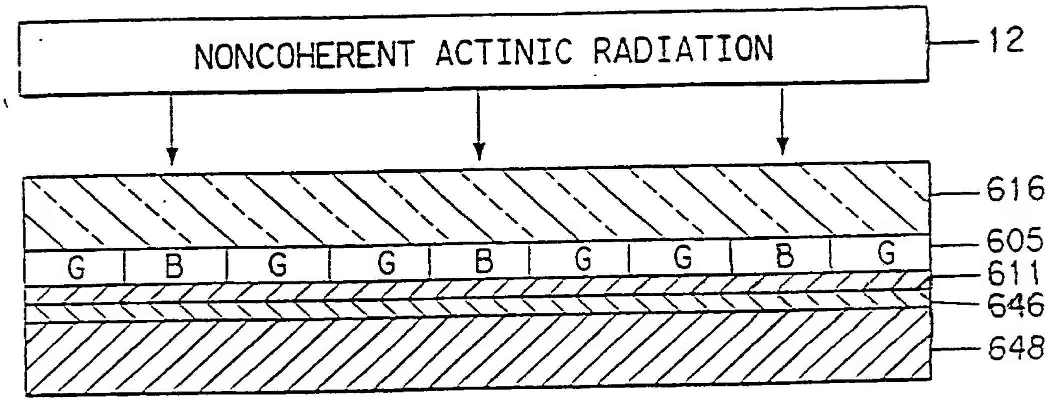

FIG.17c

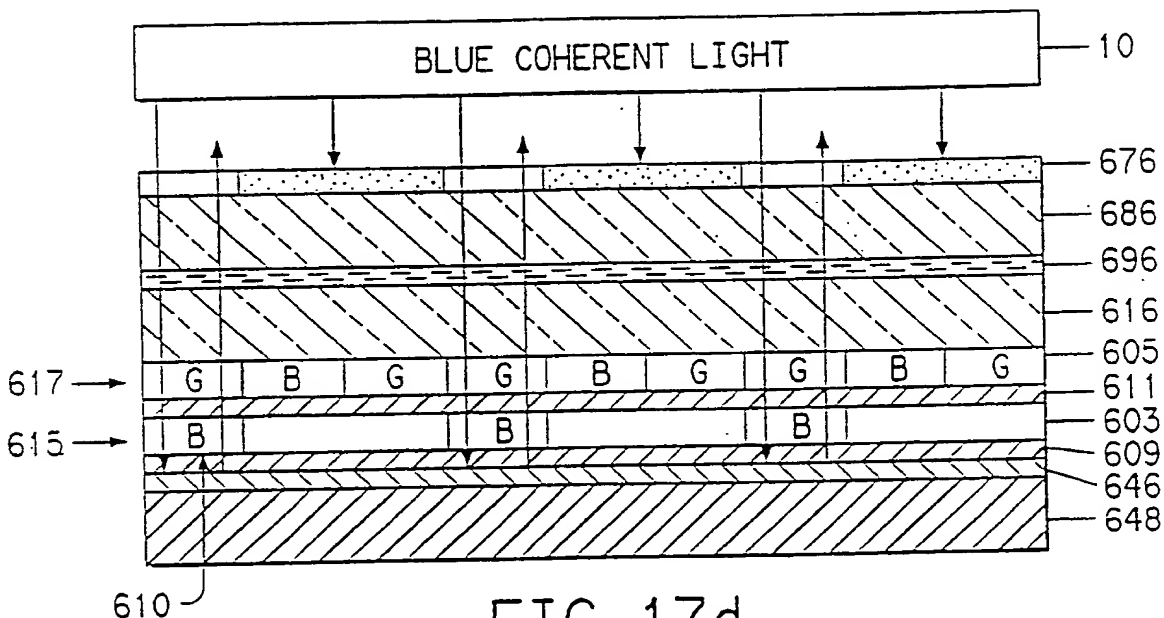

FIG.17d

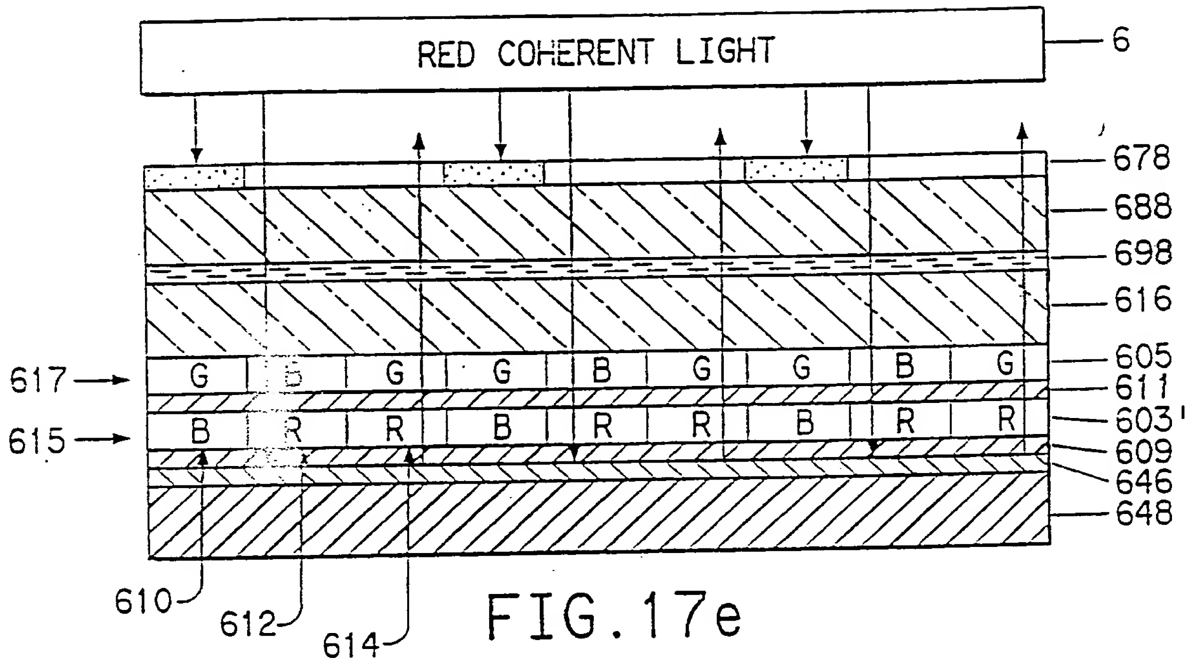

FIG.17e

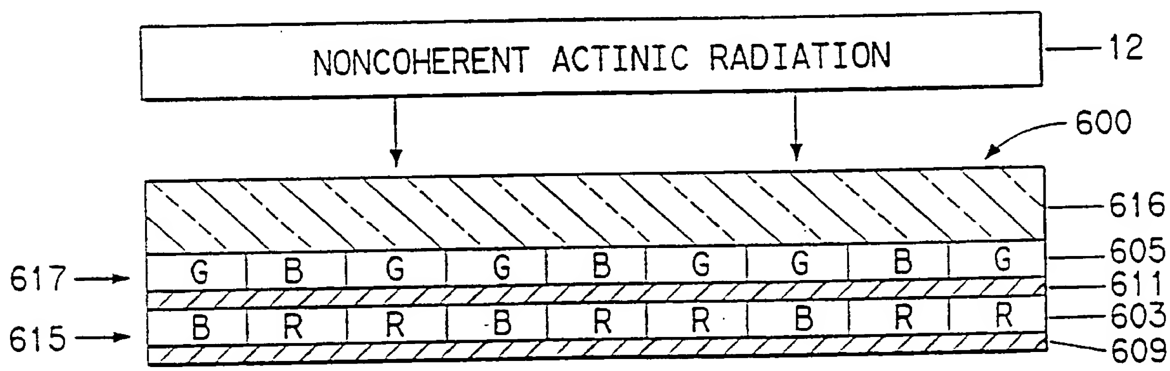

FIG.17f

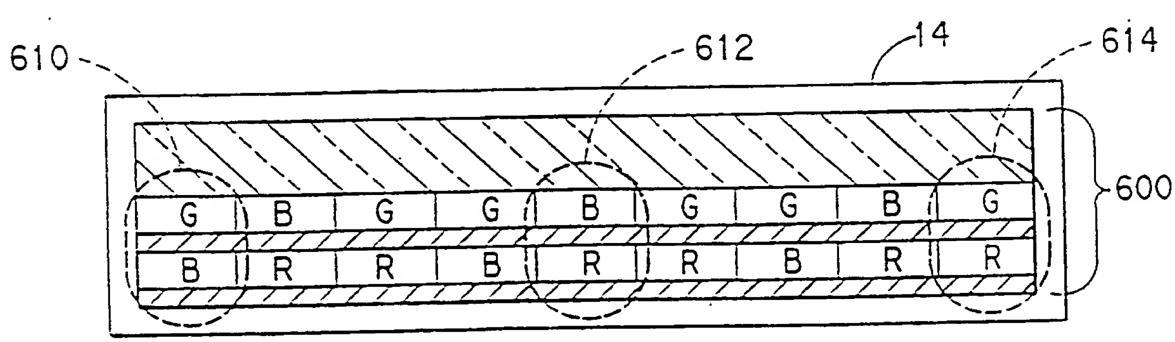

FIG.17g

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 95/06708

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B5/32 G03H1/26 G03H1/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,5 267 060 (COLTON RUSSELL F) 30 November 1993 see column 2, line 30 - column 4, line 10; claim; figures	1,2,18
Y		3,5-9, 15,16, 20,23, 24,32

Y	EP,A,0 407 773 (DU PONT) 16 January 1991 see page 3, line 13 - line 19 see page 7, line 32 - page 8, line 18 see page 9, line 20 - page 10, line 8 see page 12, line 5 - line 23 see claims 1,4,15,16	3,5-7,9, 15,16,20
A		26,28, 34,35

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 September 1995	29.09.95

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Krametz, E

2

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP,A,0 070 322 (MITSUBISHI ELECTRIC CORP) 26 January 1983 see claim 1	8,23
A		2
Y	EP,A,0 401 566 (DU PONT) 12 December 1990 see page 3, line 27 - line 39; claims 1,3	24,32
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A	SPIE VOL. 1212, PRACTICAL HOLOGRAPHY IV, 1990 pages 20-29, SMOTHERS ET AL. 'PHOTOPOLYMERS FOR HOLOGRAPHY' cited in the application see page 20, paragraph 1 - page 26, paragraph 4	1-3,9, 18,24,32
A	US,A,4 807 978 (GRINBERG JAN ET AL) 28 February 1989 see column 10, line 11 - column 12, line 22	2,8,23

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PCT/US 95/06708

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Inte[rnati]onal Application No
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